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A frequency agile RF transmitter for the entire TVWS in Libya

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***Abstract*— As a result of the admirable propagation characteristics of TV white space (TVWS) frequency band, a considerable number of wireless services could utilize the unlicensed space. Designing a flexible TVWS transmitter covering this range of the spectrum is crucial. In Libya, the TVWS consists of 51 (8 MHz band) channels covers 408 MHz of the spectrum in both fragmented VHF and UHF regions. The aim of this paper is to propose a frequency agile transmitter capable to up-sample and allocate the baseband source to the targeted channels in the radio frequency (RF) of Libya's TVWS using exponential modulation and filter bank multicarrier (FBMC) techniques. The transmitter has two design options with different sampling rates and evaluated by some performance metrics such as complexity and latency. The different implementation stages should be made without redundancy to have less complex design and strictly respect the government regulation and rules to avoid interfering adjacent channels.**

***Keywords*— TVWS, RF transmitter, filter bank, FBMC**

I. Introduction

TV White Space (TVWS) is the unused bands which appears in the spectrum as a result of the revolutionary switch from analog to digital TV. In most of the countries in the world, the TVWS is presented in the ultra-high frequency (UHF) range or both in very high frequency (VHF) and UHF ranges [1]. This spectrum has better spectral efficiency and preferable characteristics of propagation such as the signal capability of travelling long distance and in-building penetration. Thanks to that, many important applications indoor and outdoor can utilize this space such as accessing the broadband wireless in rural areas where the infrastructure is weak or not available and cellular-WLAN in urban areas, particularly in places with high density of population. Furthermore, this band can be used in wireless sensor networks to connect weather condition sensors for instance. The TVWS can be used to support modern applications such as smart-grid via TVWS [2]. In Libya, the TVWS consists of 51 channels each with 8 MHz bandwidth in both VHF band (11 fragmented channels between 47 – 230 MHz) and UHF band (40 channels in series from 470-790 MHz) [3]. The availability of the channels depends on the geographical-location which needs a frequency agile to select and change accordingly. This requires to adhere to the regulations to respect and protect incumbent users [4].

Filter Bank Multicarrier (FBMC) modulation method and orthogonal frequency-division multiplexing (OFDM) technique working at the baseband could provide frequency bands allocated to multiple users. The major disadvantage of OFDM is the shape of its spectrum. The rectangular shape in time domain of each subcarrier, outcomes in sinc function in the frequency domain, which summation causes the appearance of spectral leakage [5, 6]. In contrast, introducing FBMC using prototype filter (pulse) shape in time domain declines the leakage significantly in frequency domain. This improvement made the choice of FBMC instead of OFDM is superior. FBMC is offering higher spectral efficiency comparing to OFDM and operating up to RF is possible and appealing. This provide selectivity options for TVWS transmitters.

The initial work on multicarrier systems have been introduced in [7]. A comparison in details between OFDM and FBMC utilizing different applications have been investigated in [8]. Several approached of FBMC have been previously considered including discrete fourier transform (DFT) filter banks [9] and cosine modulated FBMC [10]. In recent past, a considerable number of FBMC schemes have been proposed with a frequency agile improvement for cognitive radio [11]. In [5], the accessibility to utilize the TVWS is presented where higher flexibility was required to target the vacant channels. In addition to the government regulation and rules, the industrial standards prior the access of TVWS such as IEEE 802.11af [12] and IEEE 802.22 has been reviewed in [13]. The computational complexity of various FBMC schemes have been explained in [14]. A very low complexity designs has been illustrated in [15, 16]. The challenge to operate TVWS for spectrum sensing in cognitive radio including regulation limitations described in [17].

As the co-channel interference is not allowed between the users. The filter design in TVWS complying with the regulations is a challenging task. The TVWS is shared with different services and devices which can be difficult to design filters avoiding the interference of other services. Having less complex design taking into consideration these factors is another challenge to be considered. The aim of this paper is to propose a transmitter design which can be operated at the entire band of TVWS in Libya to provide flexibility to change between channels without interfering the neighboring channels. The evaluation of the designs will be in terms of its performance metrics such as complexity and latency. The rest of the paper is organized as follows. Section II explains the proposed design and selectivity options. The performance metrics along with their equations are illustrated in section III. The simulation setting of Libya's TVWS transmitter with the obtained outputs and discussion of important findings exhibited in section IV. finally, the conclusion of the achieved results with recommendations can be found in section V.

II. PROPOSED DESIGN AND SELECTIVITY

The proposed design aims to simulate a transmitter able to link the TVWS channels in Libya as shown in Fig. 1 from the baseband up to the RF in their correct bands in the VHF and UHF regions. Several stages are required both in baseband and up converting the entire system to RF as shown in the proposed design in Fig. 2. Additionally, choosing the suitable sampling rate plays a major role to obtain satisfied results.

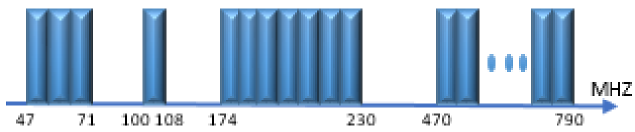


Fig. 1. TVWS channels – Libya , 11 VHF fragmented channels and 40 UHF channels.

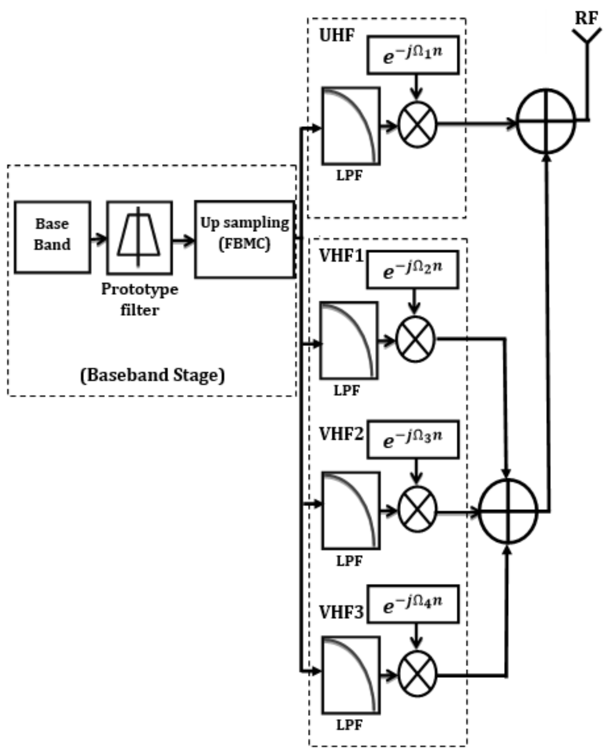


Fig. 2. Proposed RF-TVWS transmitter

A. *RF-TVWS Transmitter*

The first step to design the transmitter is to generate a prototype filter with 8MHz bandwidth as showing in Fig. 3, where the x-axis represents the frequency in (MHz) and y-axis represents the power spectral density (PSD) in (dB). The outcome of the filter will be the exact shape of one channel then multiple number of channels are created with different carriers using filter bank multi carrier (FBMC). To operate the design at the VHF and UHF ranges, up-sample the entire system to at least the Nyquist rate is compulsory. The channels of the TVWS in Libya are mainly spread in four bands in the spectrum.

Each RF-TVWS band requires a separate low pass filter to select the number of channels in that band which can then be shifted to the right (positive) location in the spectrum using exponential modulation. The 11 VHF channels require three carriers to shift the first bank of channels (three channels), the single channel in the middle and the last seven VHF channels. The 40 UHF channels needs only one carrier as a result of all the 40 UHF channels are in series. Combining the obtained channels from VHF and UHF spectrum represent the entire TVWS in Libya.

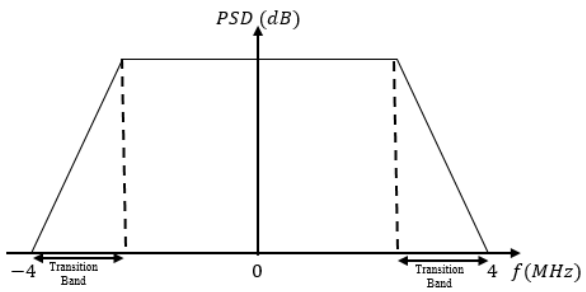


Fig. 3. Prototype filter at the baseband for a channel construction.

B. *Sampling rate selection*

The selected sampling frequency (f_s) has to be greater than or equal to the Nyquist rate. The last channel of TVWS in Libya ranged from 782 MHz to 790 MHz. This means the entire band of TVWS needs sampling rate ($f_s \geq 2 \times 790\ MHz$). Additionally, it has to be divisible by 8MHz which is the band of one channel. Taking these criteria into consideration, the first selected sampling rate is 1.584 GHz and it is the closest to the Nyquist rate. Furthermore, to get more in depth analysis and investigate the effect of sampling rate on the performance of filters, another sampling rate of 1.592 GHz has been considered in this work.

III. PERFORMANCE METRICS

The performance of the design options can be evaluated by complexity and latency. Both of these metrics are affected by the sampling rate and the implementation cost of finite impulse response (FIR) filters which include the number of the coefficients (filter length) used to satisfy the results. Moreover, the complexity is also affected by the number of carriers used in FBMC for multichannel generation.

A. Computational Complexity

The complexity of FIR filters is obtained by multiplying the sampling frequency by the length of the filter (L). The complexity of FBMC is given by $4Nlog_2N$, where N is the number of carriers [16] plus four additional multiplications for exponential modulations. Five low pass FIR filters are used in the design. One filter at the baseband with the initial sampling rate and four additional filters using the up-sampled rate. The complexity at the baseband stage is given by:

$$C|_{basband} = (L_1 \times f_s)|_{basband} \qquad (1)$$

The complexity at RF stages is given by:

$$C|_{RF} = (L_2 + L_3 + L_4 + L_5 + 4Nlog_2N + 4) \times f_s \qquad (2)$$

The entire complexity of the transmitter is measured in multiple accumulates (MACs) and obtained by the summation of both the complexity in baseband and RF stages:

$$C = C|_{basband} + C|_{RF} \qquad (3)$$

The optimum design should have the lowest possible complexity. To achieve that, there should be no redundancy in the number of filter coefficients used for filter implementation as it is proportional to the filter lengths in the numerator of the complexity equations (1) and (2).

B. Latency

The Latency of the design is affected by the sampling rate (f_s) and the filter length (L). The latency of FIR filter is the filter length divided by twice the sampling frequency. The overall latency of the transmitter is measured in second (sec) and given by:

$$Latency = \frac{L_1}{(2 \times f_s)|_{basband}} + \frac{L_2 + L_3 + L_4 + L_5}{(2 \times f_s)|_{RF}} \qquad (4)$$

The sampling frequency is in the denominator of the latency equation (4) and in the numerator of complexity equations (1) and (2). Thus, there is a trade-off between complexity and latency unless the effect of the increase in the sampling rate was less comparing to the increase of the filter lengths which will be investigated in section V.

IV. Simulation Setting and Results

The first step in the baseband is to design a prototype filter to shape one channel with 8 MHz bandwidth from -4 MHz to 4 MHz as shown in Fig. 4. The sampling rate at this stage is 8MHz. Upsampling the entire system is required to have multiple channels using FBMC presented in Fig. 5. To modulate the three bands of VHF channels, initially each band requires its own FIR Low Pass Filter (LPF) illustrated in Fig. 6. Shifting each band of VHF channels to the correct location in the spectrum by exponential modulation outlined in Fig. 7. Selecting the 40 channels to be shifted to UHF region requires only one FIR LPF demonstrated in Fig. 8. The modulated 40 UHF channels in their position in the spectrum outlined in Fig. 9. The entire TVWS channels in Libya is obtained by combining the 51 channels of VHF and UHF bands as shown in Fig. 10.

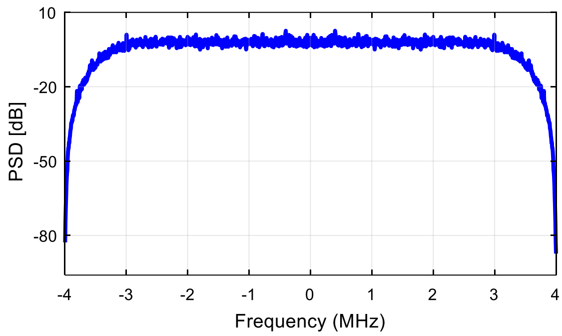


Fig. 4. Prototype filter, representing one channel with 8MHz bandwidth.

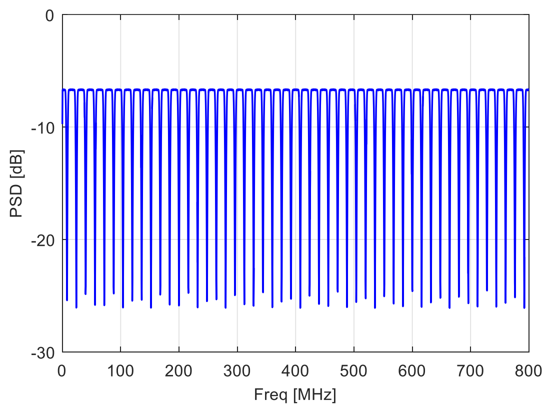
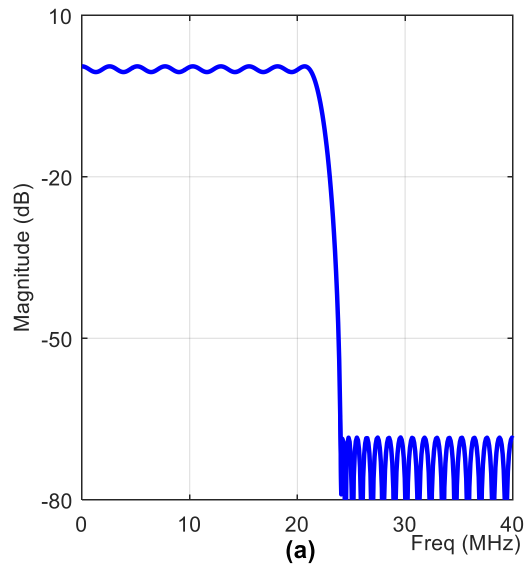


Fig. 5. A bank of closely spaced channels with 8MHz band each.



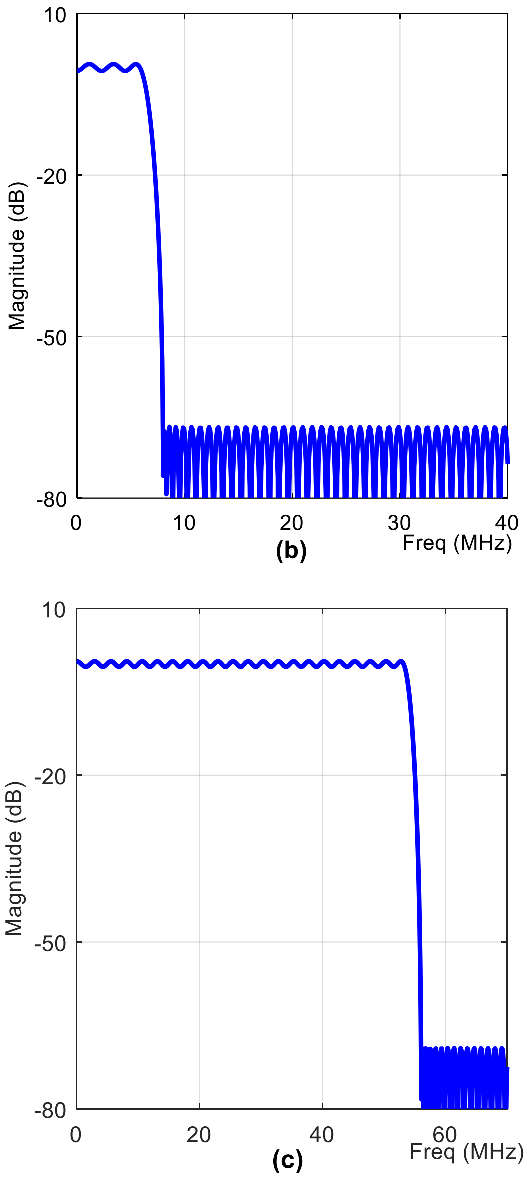


Fig. 6. LPF-FIR filter responses to extract: (a) 3 channels, (b) A single channel and (c) 7 channels.

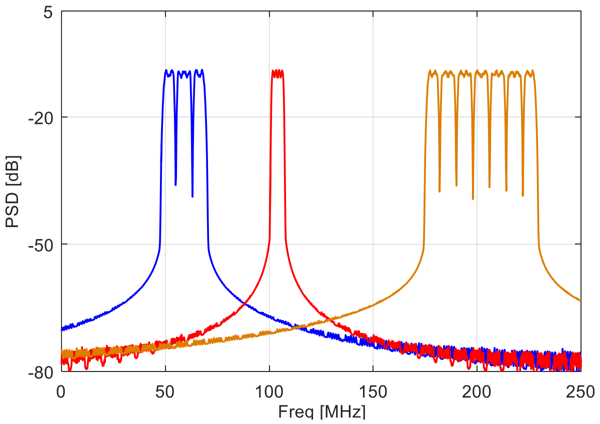


Fig. 7. TVWS – 11 VHF channels, Libya.

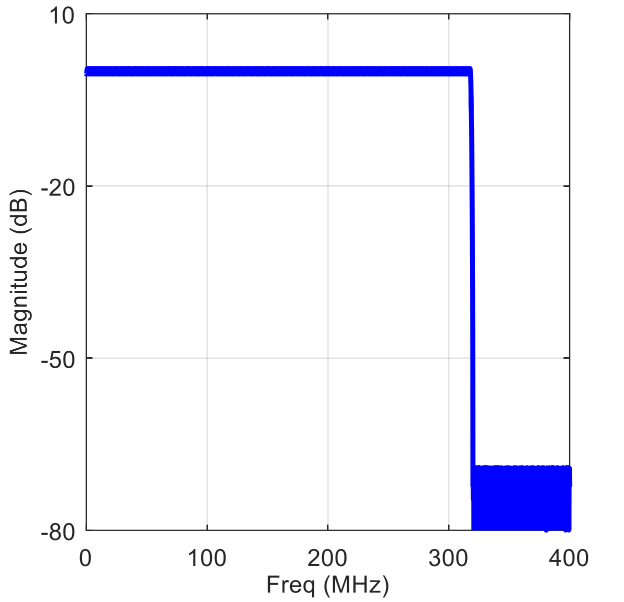


Fig. 8. LPF-FIR filter response to extract 40 channels.

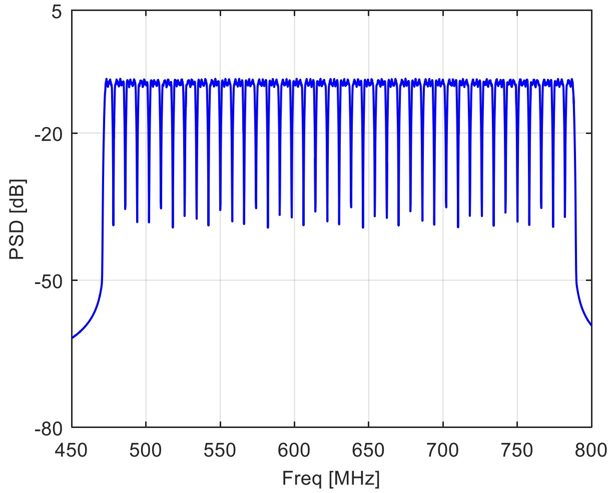


Fig. 9. TVWS – 40 UHF channels, Libya

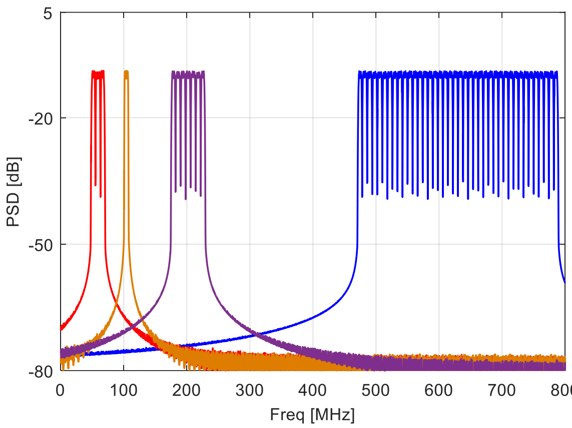


Fig. 10. The entire 51 TVWS channels, Libya.

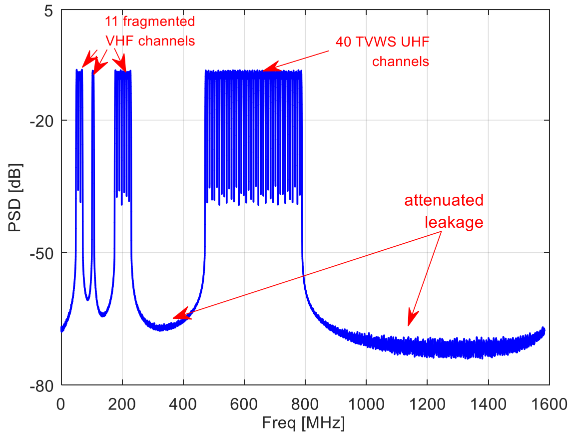


Fig. 11. The Libya's TVWS channels (peaks) and the attenuated leakage up to the chosen sampling rate.

The performance of the two design options using sampling frequency 1.584GHz and 1.592GHz is summarized in Tab. I. The spectral leakage have been attenuated with accepted values for the entire spectrum up to the sampling frequency outlined in Fig. 11. The performance metrics of both designs was affected by the sampling rate and the filters implementation cost especially the filter L_4 which used for the single channel from 100-108 MHz in the VHF range. This filter requires more coefficients and was not relaxed due to its narrow width comparing to other filters in other bands which contains more channels. It is also evidence that as the sampling rate increases, a trade-off between complexity and latency appears.

TABLE I. PERFORMANCE MEASURE

		Design Options	
		Design (1)	***Design (2)***
$(f_s)\|_{basband}$ (MHz)		8	8
Up-sampling factor		198	199
$(f_s)\|_{RF}$ (GHz)		1.584	1.592
filters lengths	L_1	13	13
	L_2	1417	1424
	L_3	1306	1313
	L_4	1763	1772
	L_5	1345	1351
Complexity (GMACs)		1.881×10^4	1.901×10^4
Latency (μsec)		2.6531	2.6530
Adj-channels leakage (dB)		-55.26	-55.21

V. Conclusion

A transmitter with two possible sampling rate options 1,584 GHz and 1.592 GHz satisfying the Nyquist theorem up to VHF and UHF ranges has been designed. The design covers the entire TVWS band in Libya and successfully accommodates 51 channels, 8MHz band each in their place in the spectrum. The spectral leakage has been attenuated to feasible values respecting the adjacent channels. The performance of each design has been evaluated by both complexity and latency. A trade-off between them has arose out as a result of increasing the sampling rate in the design option (2). Having fragmented channels in three separated VHF regions requires additional filter for each band causes a massive increase in the complexity which is proportional to the number of used filters and their lengths. The complexity of the transmitter can be reduced significantly by targeting the bands which contains more channels such as UHF band with 40 channels in series and the third VHF band with 7 channels in series. Averting the remaining 4 VHF fragmented channels in any future RF transmitter design for Libya's TVWS would be a wise decision on account of their major cost on the system.

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