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DESIGN AND REALIZATION OF LESS-COMPLEX WAVELET-BASED TRANSCEIVERS

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Abstract

Wavelet-based transceivers are designed and realized in this paper with the less-complex structure using the idea of wavelet packet multicarrier modulation (WPMCM) system. A proposed WPMCM system is designed using a special type of IIR filter banks called bi-reciprocal lattice all-pass digital filter bank (BLAPDFB). A two-parallel-channel type of IIR filter banks is designed with approximate linear phase starting from a 4^{th} order all-pass section in one channel and a 3rd order pure delay in the other. The proposed design is then realized with reduced the number of required filter coefficients. The transfer function of the first-scale structure of the designed IIR filter is derived and the resulting magnitude and phase responses of the designed IIR filter are plotted for investigations. A modified less-complex structure is realized and compared with some other realizations including the conventional orthogonal frequency division multiplex (OFDM) system. The comparison shows the less-complexity property of the proposed WPMCM structure.

Keywords: Approximate linear phase property, Bi-Reciprocal lattice all-pass digital filter bank (BLAPDFB), IIR filter banks, Less-complex structure, Orthogonal frequency division multiplex (OFDM) system, Wavelet packet multicarrier modulation (WPMCM) system.

1. Introduction

It has become common to employ filter bank based multicarrier techniques in wireless communication systems in order to provide multiple access or increase system capacity. Orthogonal frequency division multiplex (OFDM), discrete multi-tone (DMT), and wavelet packet multicarrier modulation (WPMCM) are some models of such systems [1].

A wavelet packet filter bank system is inquired as a multicarrier modulation system (MCM). Such a system has many merits over the conventional OFDM systems. The major disadvantage of the OFDM is that the fast Fourier transform (FFT) process in OFDM decomposes the signals into basis trigonometric functions such as sines and cosines, which create high side lobes outcome rectangular window used. Moreover, the pulse shaping function used to modulate each subcarrier stretches to infinity in the frequency domain.

By contrast, the wavelet packet transforms (WPTs) have longer basis functions and can offer a higher degree of side lobe suppression with improved performance against channel effects. The long wavelet basis in WPMCM can permit for better frequency localization of subcarriers [2]. Nevertheless, the length of wavelet basis is much longer than the interval of a symbol causes some overlap in the time domain with subsistence of their orthogonality.

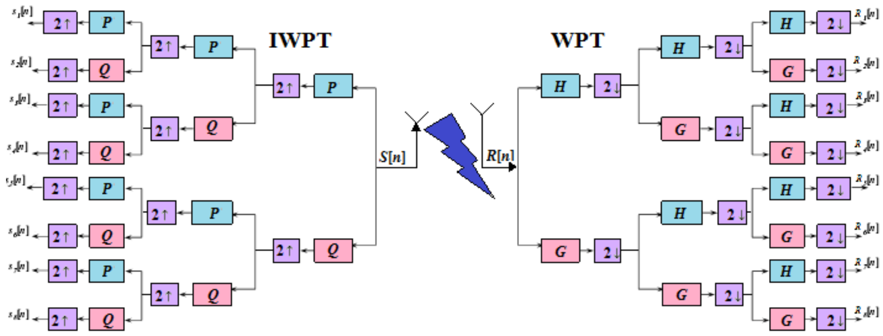
Therefore, there is no need to use the cyclic prefix to mitigate the inter-symbol interference, which is a major disadvantage in the OFDM that causes bandwidth inefficiency, where cyclic prefix occupies nearly 20% to 25% of total bandwidth [3, 4]. Thus, WPMCM provides great orthogonality between subcarriers and improves imperfection in bandwidth wastage by having excellent spectral containment.

In addition, WPMCM can be realized in a faster model and processed by less-complex computations, leading to a transmission power reduction. Furthermore, WPMCM has the advantage of analysing signals in WPT by representing them in time-frequency domain rather than just the frequency domain as in FFT. That’s why WPMCM has emerged as excellent candidates for MCM in wireless communication systems [5, 6].

WPMCM are generally applied where WPT is examined. The signals are closely and scientifically analysed at different scales by using a multi-scale filter bank. The filtering operations are used to change the resolution of the signal. That is a measure of the quantity of detail information in the signal. While the up and down sampling operations are applied to change the scale in the signal [7].

The classical WPMCM transceiver system utilizes inverse wavelet packet transform (IWPT) at the transmitter side and WPT at the receiver side. The IWPT is realized by WP synthesis filter bank, which joins different parallel streams into a sole signal $S[n]$.

This composite signal is subsequently separated into simpler compounds at the receiver using WPT, which is implemented WP analysis filter banks. Figure 1 shows the classical WPMCM structure of a transceiver with three-stage decomposition (8 channels) [8].



(a) Synthesis filter bank transmitter side. **(b) Analysis filter bank receiver side.**

Fig. 1. Classical WPMCM based transceiver with three-stage decomposition (8 channels).

The foundation of a WPMCM basis starts with a pair of quadrature mirror filters (QMFs) at the receiver $\{h[n], g[n]\}$ half- band low and high pass analysis filter, respectively. If the length of each filter equals to L, the following condition is satisfied [9].

$$g[n] = (-1)^n \, h[L - n - 1] \tag{1}$$

On the other hand, it has a pair of synthesis filters $\{p[n], q[n]\}$ that are employed to generate the wavelet packet carriers for modulation of data at the transmitter.

For perfect reconstruction (PR) and due to the fact of occurrence the mirror image symmetry around the frequency $\omega = \frac{\pi}{2}$ amid of both $H(e^{j\omega})$ and $G(e^{j\omega})$ as depicted in Fig. 2 [10]. The analysis and synthesis filter banks must guarantee conditions as:

$$G[z] = H[-z]\,, P[z] = H[z] \text{ and } Q[z] = -H[-z] \tag{2}$$

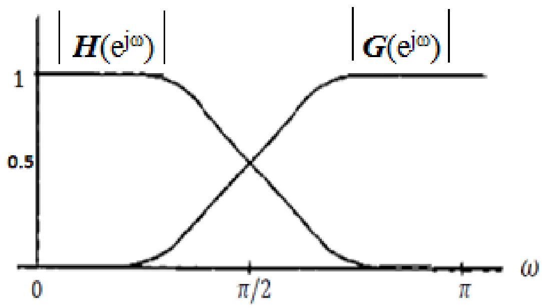


Fig. 2. Frequency responses of analysis filters [10].

In addition to achieving both orthonormality properties and PR, the analysis and synthesis filters must satisfy the following two conditions [11]:

$$H[-z]P[z] + G[z]Q[z] = 0 \tag{3}$$

and

$$H[z]P[z] + G[z]Q[z] = 2z^{-1} \quad (4)$$

Any modulation signal in WPMCM transceiver system can be comprised of a sum of modulated wavelet packet coefficients ζ_l^p weighted with complex data $a_{u,k}$ (known as multicarrier symbols). This signal $S[n]$ can be expressed as follows [12]:

$$S[n] = \sum_u \sum_{k=0}^{N-1} a_{u,k}\zeta_{log_2(N)}^k(n - uN) \quad (5)$$

Each wavelet packet coefficient $\zeta_l^p\ [n]$ in Eq. (5), is calculated by convolving the h and g filters with the wavelet packet coefficients from a previous level as shown in Eqs. (6) and (7). And so on, this convolution process is repeated for all wavelet packets until reaching the desired resolution. According to Tabaa [12], this act explained obviously in wavelet packet analysis and is well shown in Fig. 1(b).

$$\zeta_{l+1}^{2p}[n] = \sqrt{2}\sum_k h[k]\zeta_l^p[2n - k] \quad (6)$$

$$\zeta_{l+1}^{2p+1}[n] = \sqrt{2}\sum_k g[k]\zeta_l^p[2n - k] \quad (7)$$

With a reversed-repeated method, a wavelet packets synthesis filter bank can reconstruct the wavelet packets as in Eq. (8).

$$\zeta_l^{2p}[n] = \sum_k h[k]\zeta_{l+1}^{2p}[2n - k] + \sum_k g[k]\zeta_{l+1}^{2p}[2n - k] \quad (8)$$

This performance is called wavelet packet synthesis demonstrated in Fig. 1(a) [12]. The whole structure of the WPMCM transceiver system is depicted in Fig. 3.

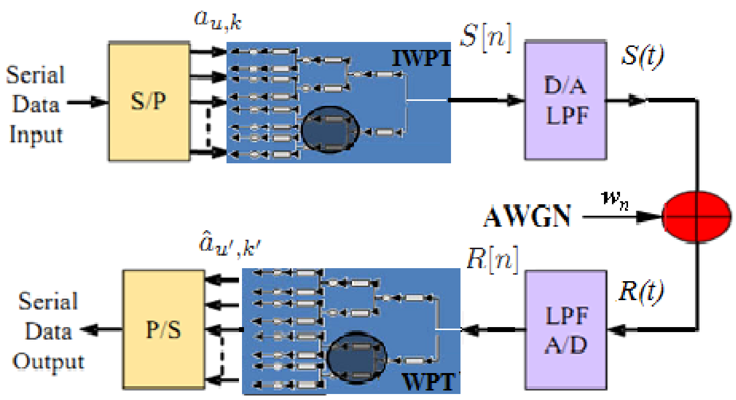


Fig. 3. WPMCM transceiver system.

The major problem of the WPMCM-transceiver system is its increasing complexity with the increase of number of channels. In this paper, a new WPMCM-transceiver system structure is designed using a special type of IIR filter bank called bi-reciprocal lattice all-pass digital filter bank (BLAPDFB). BLAPDFB as the basic framework of such IIR filter bank is realized in this paper with less-complexity. In addition, such designed IIR filter bank has the approximate linear phase property, which guarantees the near perfect reconstruction (NPR) attributes of signals throughout all parts of the transceiver system.

This paper is organized as follows: the principles of multicarrier systems (such as OFDM and WPMCM) are introduced in Section 1 with the comparison of their properties and performance. Section 1 also provides a foundation of the classical WPMCM system with their structures and investigations on their analysis and synthesis filter banks to guarantee perfect reconstruction conditions are also contained. In Section 2, the proposed filter bank design model is proposed for the design of a WPMCM system. A modified 4th order BLAPDF IIR filter is then shown in Section 2 to achieve a new WPMCM system with less complexity. The whole less-complex structure of the WPMCM based trans-multiplexer system is accomplished in Section 3. Section 4 is dedicated to the results showing the complexity comparison of the proposed WPMCM system and many others including OFDM. Finally, Section 5 concludes this paper.

2. The Proposed IIR Filter Bank Model

To evidence near perfect reconstruction (NPR) attributes, the proposed filter bank is designed to approximately fulfil the PR conditions. An approximate linear phase (NPR) IIR filter is be employed in the case of filter bank multicarrier (FBMC), which is utilized in the WPMCM. Trans-multiplexer configuration for synthesis filter bank in the transmitter and analysis filter bank in the receiver to simulate a dual channel filter bank.

In this paper, a particular type of IIR filter banks is designed and realized as wavelet-based transceivers. The bi-reciprocal lattice all-pass digital filters (BLAPDF) [13] are utilized as the basic framework of such IIR filter banks and are designed from a 4th order IIR wavelet filter bank, which will be utilized here in an approximate linear phase model for the design of a WPMCM transceiver system based on the model as introduced by Abdul-Jabbar and Saadi [14].

2.1. Design of proposed IIR filter bank

The proposed low-pass filter branch used in constructing the first scale structure of the BLAPDFB is demonstrated in Fig. 4. It comprises of two parallel channels. One of these parallel channel, the upper branch, consists of a 4th order all-pass section even order ($2N = 4$) and made up of a cascade of two similar 2nd order all-pass sections to reduce the computation burden by reducing the number of required filter coefficients (number of multipliers). This idea is employed to achieve a design with less-complex system realization. While the lower branch consists of an uncomplicated odd order ($2N$-1 = 3) 3rd order pure delay [14].

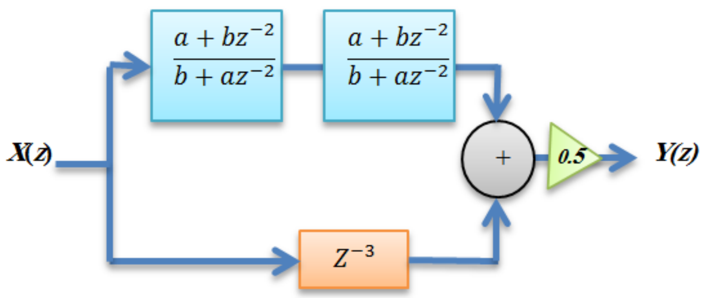


Fig. 4. Bi-reciprocal lattice WDF structure.

It is obvious that the transfer function of the designed low-pass filter of Fig. 4 will acquire a 7th order and can be written as:

$$H(z) = \frac{Y(z)}{X(z)} = \frac{1}{2}\left[\left(\frac{a+bz^{-2}}{b+az^{-2}}\right)^2 + z^{-3}\right] \quad (9)$$

where *a* and *b* are the merely two all-pass filter coefficients to terminate the complete filter design. Consequently, the comprehensive frequency response of such low pass filter can be given by:

$$H(z) = \frac{Y(e^{i\omega T})}{X(e^{i\omega T})} = \frac{1}{2}\left[\left(\frac{a+be^{-j2\omega T}}{b+ae^{-j2\omega T}}\right)^2 + e^{-j3\omega T}\right] \quad (10)$$

The design is simply finalized if the values of the coefficients a and b in Eq. (10) are resolved. The coefficients a and b are determined by allowing the transfer function of the designed low-pass filter of Fig. 4 to simulate the following transfer function of the 4th order low-pass linear phase FIR filter given by Abdul-Jabbar and Hamad [15].

$$H_f(z) = 0.001275 + 0.146z^{-1} + 0.7092z^{-2} + 0.146z^{-3} + 0.001275z^{-4} \quad (11)$$

therefore,

$$H_f(e^{j\omega T}) = 0.001275 + 0.146e^{-j\omega T} + 0.7092e^{-j2\omega T} + 0.146e^{-j3\omega T} + 0.001275e^{-j4\omega T} \quad (12)$$

where *T* is the sampling period and can be normalized to 1. The least square method solution is applied as shown in the following error equation:

$$E = \sum_{\omega=0}^{\pi}\left[H(e^{i\omega T}) - H_f(e^{i\omega T})\right]^2 \quad (13)$$

To have a minimum error value, an optimization algorithm called Smart Bacterial Foraging Algorithm (SBFA) [16] is applied to solve Eq. (13). Thus, the values of the coefficients a and b are obtained to reflect a minimum value of error. Subsequently, activating the SBFA gives the following results: *E* = 0.0031, *a* = 0.024 and *b* = 0.5074.

Consequently, the transfer function of the first scale structure of the designed BLAPDFB can be expressed as:

$$H(z) = \frac{1}{2}\left[\left(\frac{0.024+0.5074z^{-2}}{0.5074+0.024z^{-2}}\right)^2 + z^{-3}\right] \quad (14)$$

2.2. Reducing the order of the designed IIR filter

An uncomplicated form of Eq. (14) can be rewritten in the following form with a single coefficient realization:

$$H(z) = \frac{1}{2}\left[\left(\frac{0.0473+z^{-2}}{1+0.0473z^{-2}}\right)^2 + z^{-3}\right] \quad (15)$$

To reduce the order of the filter to the half, the input samples are separated into odd and even samples, in other words are decimated by two. This simplified filter structure can be succeeded without any effect on the phase response, that framework called poly-phase [17]. Hence, the modified reduced order (4th order) BLAPDF IIR filter bank shown in Fig. 5 can be drawn from the 7th order BLAPDF of Fig. 4. Therefore, Eq. (15) can be reduced after down sampling the following Eq. (16).

$$H(z) = \frac{1}{2}\left[\left(\frac{0.0473+z^{-1}}{1+0.0473z^{-1}}\right)^2 + z^{-2}\right] = \frac{1}{2}\left[\left(A(z^{-1})\right)^2 + z^{-2}\right] \quad (16)$$

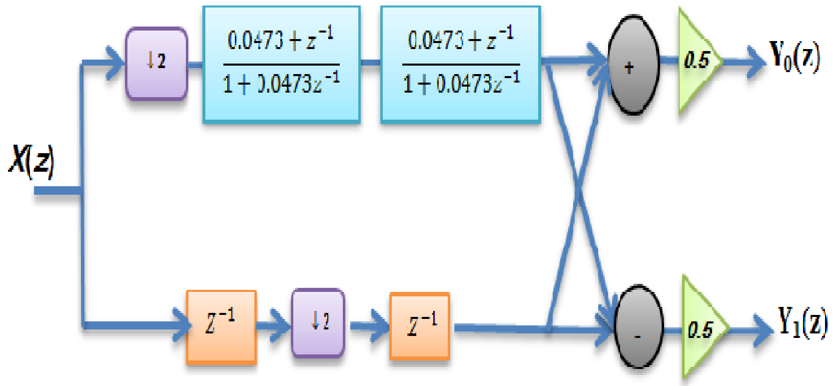
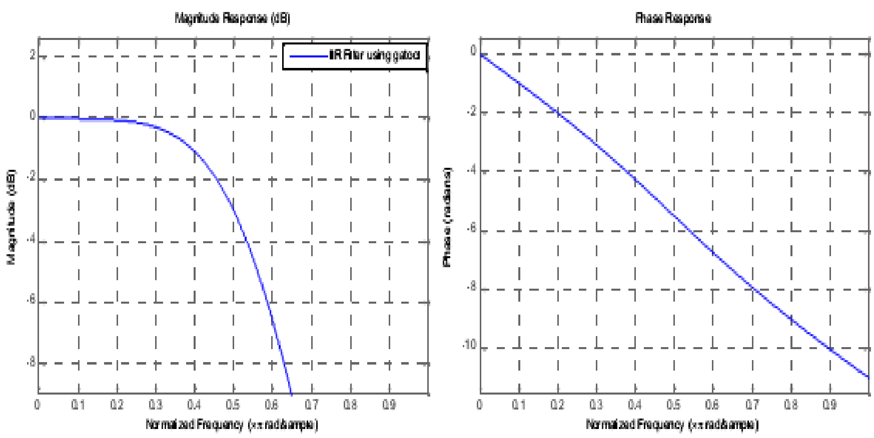


Fig. 5. A modified 4th order BLAPDF IIR filter bank (analysis side).

2.3. The resulting magnitude and phase filter responses

The resulting magnitude and phase responses of the designed IIR filter in Eq. (16) are plotted in Figs. 6(a) and (b). It can be seen that Fig. 6(b) reveals an approximate linear phase processing stage, especially in the passband [18].



(a) Magnitude response. **(b) Phase response.**

Fig. 6. Frequency response of the 4th order low pass BLAPDF filter (upper branch of Fig. 5).

This type of filter is called half band filter, since all the odd coefficients in the transfer function of the upper branch are equal to zero, so it will reduce the computations, the sampling rate to a half and the ripples in pass-band, reflecting a better attenuation in the stop band.

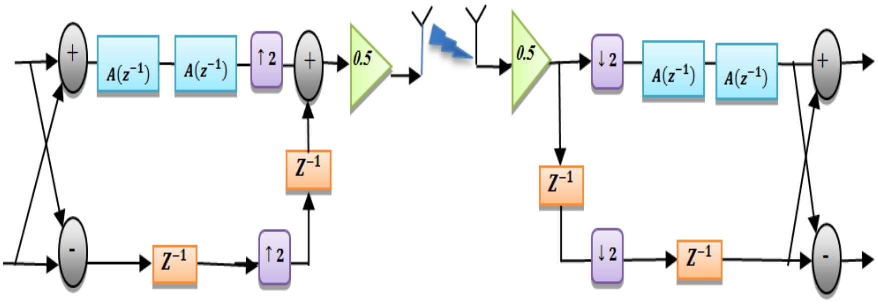
The comparable transfer function of the high pass filter (lower branch of Fig. 5) can be found from low pass filter by subtracting the lower branch from the upper branch [19] rather than adding them. It can be written as:

$$G(z) = \frac{1}{2}\left[\left(\frac{0.0473+z^{-1}}{1+0.0473z^{-1}}\right)^2 - z^{-2}\right] = \frac{1}{2}\left[\left(A(z^{-1})\right)^2 - z^{-2}\right] \quad (17)$$

3. Less-Complex Structure of WPMCM based Trans-Multiplexer System

The first step in designing WPMCM is established by utilizing the 2 channels all-pass filter banks $\{h[n], g[n]\}$, formulated above for the three-level decomposition as shown in the trans-multiplexer in Fig. 1.

A less-complex lattice structure realization of such WPMCM with 2 channels all-pass filter bank is depicted in Fig. 7 applying the poly-phase conditions. In this realization, the construction of multichannel IIR filter banks can be efficiently achieved with approximate linear phase in addition to the absolute elimination of both the amplitude distortion and aliasing error.



(a) Synthesis side. **(b) Analysis side.**

Fig. 7. Lattice poly-phase WPMCM structure realization of the all-pass IIR filter bank (2 channels).

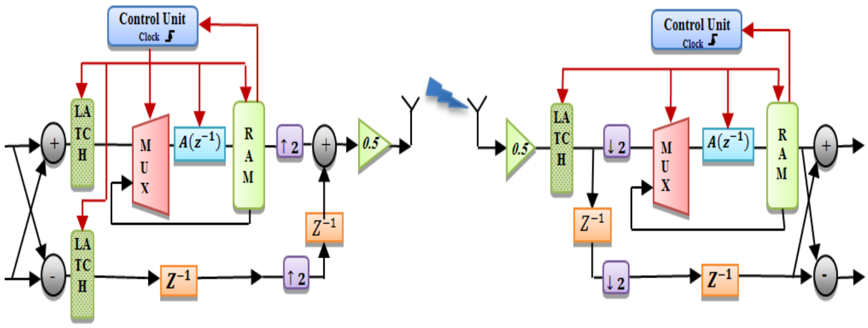
A final implementation of the structure of Fig. 7 is shown in Fig. 8 using a bit-serial technique that is one of common implementation techniques in DSP. This technique becomes the most suitable to be used when the area is considered a serious factor of merit for the designer to have an area-efficient implementation. On the other hand, the only defect of such implementation is the insignificant clock frequency while a high throughput is usually required [20]. The goal of bit-serial realization is to take advantage of less complex implementation of the upper branch of the filter by utilizing only one all-pass section to perform the whole processing, since the output of this all-pass section is fed back to its input in place of using another all-pass section to fulfil the same processing requirement.

Latches will be used on both sides (analysis and synthesis) to hold over the original signal stream. The multiplexers on both sides will decide via a control unit, which one of the following two signals will be passed: the original signal or the RAM data. In both Figs. 7 and 8, the 0.5 multiplier values outside synthesis and analysis structures (in the path to/from antennas) can be simply realized as one-bit delayers.

4. Results and Comparative Study

After having the lattice poly-phase WPMCM structure realization of Fig. 7 and area-efficient implementation of the proposed WPMCM structure using bit serial technique of Fig. 8, the total number of multipliers, adders and delayers in these two structures is computed. A comparison is made among the following different realizations: Daryabeigi and Dehkordi [16] mentioned that WPMCM is with 4th order FIR filter. [16] and based on studies by Abdul-Jabbar and Hamad [15] that WPMCM with 7th order IIR filter, the proposed 4th order lattice poly-phase WPMCM structure of Fig. 7, WPMCM structure using bit serial technique of Fig. 8 and finally 8-channle conventional OFDM. It should be noted that Table 1 summarize this comparison for a 3-level decomposition (i.e., 8 channels).

From Table 1, it can be noticed that the number of multipliers (which are the most expensive building blocks) is the minimal for BLAPDF IIR bit-serial implementation among different transceiver systems. This can guarantee the less-complex property of the proposed WPMCM system at the expense of the processing time, which takes a time delay of 42T. This increase in time delay can be overcome using a fast chip in implementation.



(a) Synthesis side. **(b) Analysis side.**

Fig. 8. An area-efficient implementation of the WPMCM structure (2 channels) using bit serial technique.

Table 1. Comparison of complexity for different transceiver systems.
*** τ_m is the time for single multiplication process.**

System bases	Filter length	No. of multipliers	No. of additions	No. of delay units	Time delay
WPMCM using 3-level decomposition of FIR filter by Daryabeigi and Dehkordi [16]	4	112	112	280	60T
WPMCM using 3-level decomposition of IIR filter by Abdul-Jabbar and Hamad [15]	7	28	91	154	48T
WPMCM structure using 3-level decomposition of Fig. 7	4	28	91	84	24T
WPMCM structure using 3-level decomposition of Fig. 8 (bit-serial)	4	14	63	98	42T
OFDM (8 channels)	---	24	48	0	-- τ_m

5. Conclusion

A less-complex structure in WPMCM system has been designed and realized in this paper based on a special type of IIR filter banks called bi-reciprocal lattice all-pass digital filter bank. The design has been achieved with approximate linear phase for perfect reconstruction conditions. The proposed design has been realized with less-complex structure and then compared with other conventional realizations including OFDM system. The comparison has proved the superiority of the proposed WPMCM-transceiver structure in terms of less-complexity property. The comparison among different WPMCM structures has been accomplished based on total number of multipliers, adders and delayers, utilized in those structures.

Nomenclatures

$a_{u,k}$	Multicarrier symbols
E	Error
H	Low pass analysis filter
G	High pass analysis filter
L	Filter length
P	Low pass synthesis filter
Q	High pass synthesis filter
S	Signal
T	Sampling period, s
X	Input signal to the filter
Y	Output signal to the filter
z^{-1}	Delay

Greek Symbols

ξ	Wavelet packet coefficient
τ_m	Time for single multiplication process, s
Ω	Frequency, Hz

Abbreviations

BLAPDFB	Bi-Reciprocal Lattice All-Pass Digital Filter Bank
FBMC	Filter Bank MultiCarrier
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
IIR	Infinite Impulse Response
IWPT	Inverse Wavelet Packet Transform
MCM	MultiCarrier Modulation
NPR	Near Perfect Reconstruction
OFDM	Orthogonal Frequency Division Multiplex
PR	Perfect Reconstruction
QMF	Quadrature Mirror Filter
SBFA	Smart Bacterial Foraging Algorithm
WPMCM	Wavelet Packet MultiCarrier Modulation
WPT	Wavelet Packet Transforms

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