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SPECTRALLY EFFICIENT 8 BY 8 MIMO BASED PHYDYAS FILTERED OQAM-MODULATED FBMC

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Abstract

We developed a spectrally efficient 8 by 8 MIMO based OQAM-modulated FBMC using PHYDYAS filter as opposed to Hermit filter which enabled the concentration of energy in time domain, rapid decaying in the frequency domain to reduce Inter-carrier interference (ICI), and flexibility with respect to overlapping factor, R. The computation involved in the design and implementation of PHYDYAS filter is also less compared to Hermit filter. Hadamard coding scheme enabled bi-orthogonality by restoring the orthogonality in the imaginary field of the complex data symbol, thereby availing both the imaginary and real components for transmission. The complex data symbol were transmitted by employing Space-Time Transmission Scheme which cancelled the imaginary intrinsic interference developed at the receiver side which also augment the compatibility of the OQAM-modulated FBMC complex data symbols with the MIMO system. The spectrally efficient system developed is a result of the collective advantageous properties of the PHYDYAS filter, the Hadamard coding scheme, and the space-time transmission scheme.

Keywords: *FBMC, FFT, Hadamard, IFFT, MIMO, PHYDYAS filter, STTS.*

INTRODUCTION

The present generation of wireless telecommunication network and the next generation, to a greater extent, require the optimal usage of the available radio spectrum to meet up the advancement in network scenarios coupled with the excessive demand in efficient data transmission[1]. The spectral efficient superiority of Filter Bank Multicarrier Modulation Offset Quadrature Amplitude Modulation (FBMC-OQAM) and the superior capacitive property of 8 by 8 Multiple Input Multiple Output (MIMO) systems when collectively utilized produces a spectrally efficient MIMO based OQAM-modulated FBMC system which has a high capacity gain compared to conventional MIMO/FBMC-OAQM[2]. FBMC-OQAM data symbols are transmitted over a large MIMO system using Space Time Transmission Scheme (STTS) which cancels the imaginary intrinsic interference developed at the receiver end of the system transceiver[3] due to the intersection of the filter response of neighboring sub-channels in the imaginary domain of complex data symbols and has a degrading effect to the system's overall performance[2]. This however, is done after restoring orthogonality in the imaginary domain of the complex data symbol[4]. The filter used for the multicarrier modulation is PHYDYAS filter whose choice was informed by the compactness of energy in time domain, quick decaying in the frequency domain to mitigate Inter-carrier interference (ICI), and also flexibility with respect to overlapping factor The computation involved in the design and implementation of PHYDYAS filter is less compared to Hermit filter[5]. This is because the FFT and IFFT sizes of the system with respect to PHYDYAS filter are maintained[6]. This research used PHYDYAS filter as opposed to Hermit filter in developing a spectrally efficient MIMO OQAM-modulated FBMC.

METHODOLOGY

The methodology adopted in carrying out this research work is as follows:

I. Developing FBMC-OQAM data model using PHYDYAS filter for transmission over an 8 by 8 MIMO system which involves the following steps:
    A. Developing a matrix based FBMC-OQAM data model.
    B. Restoring orthogonality in imaginary domain by Hadamard coding scheme.
II. Enhancing the compatibility of MIMO with FBMC-OQAM system by the cancelation of imaginary intrinsic interference which involves the following steps:
    A. Using STTS to cancel the imaginary interference of the FBMC-OQAM system.
    B. Transmitting the FBMC-OQAM data symbols over the MIMO system.

III. Determining the spectral efficiency of the developed system and validating the result with a system developed using a Hermit filter.

I- Developing the FBMC-OQAM data Model

In a multipath fading channel, the components of the direct ray [$x_D(t)$] and all the indirect rays $x_{R,N}(t)$ add up to give the received complex multicarrier signal, y(t) [3]:

$$y(t) = \sum_{n=0}^{N-1} \rho_n e^{j\phi_n} x(t-\tau_n) \tag{1}$$

where, ω_0 is the angular frequency, ρ_n is the differential amplitude between the direct ray and the reflected ray and is a real number, τ is their differential time

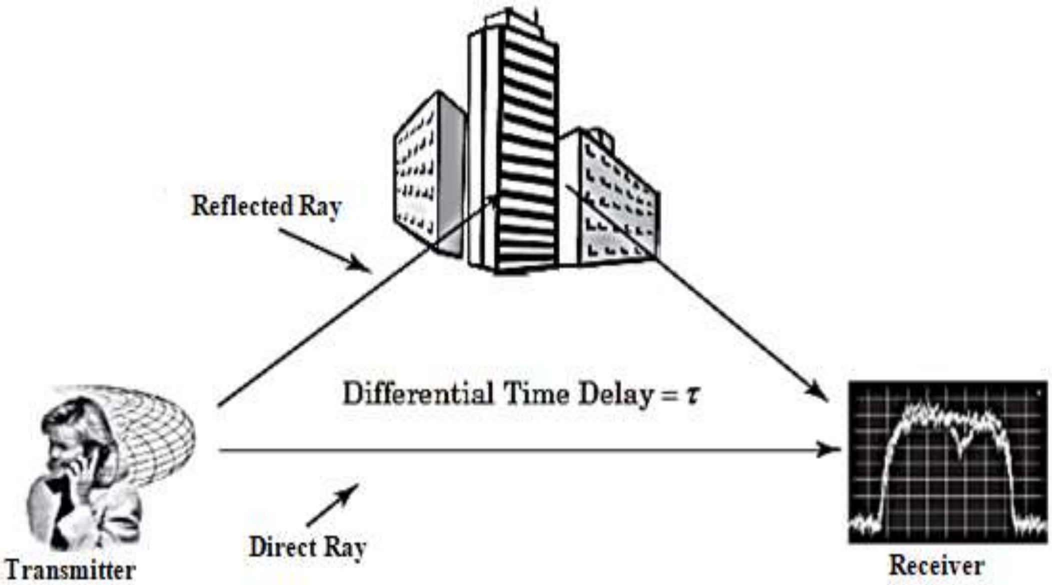

Figure 2.1: Signal Transmission in a Multipath Fading Channel[3]

A. Developing a Matrix Based FBMC-OQAM Data Mode

The multicarrier signal of equation (1) was modulated to transmit and receive offset QAM symbols, hence the name OQAM. The modeling of the FBMC signal is as follows[7]:

i. OQAM Preprocessing: The complex multipath signal of equation (1) was preprocessed and sampled for the offset quadrature amplitude modulation with the sampling set-up parameters given in Table 1 [7].

Table 1: Setup Parameters for OQAM Preprocessing of FBMC Signal[7]

S/N	Parameter	Numerical Value	Comment
1	Subcarriers (L)	24	Subcarriers for each symbol in FBMC
2	Symbols (K)	8	From 2 to a limit of 8 symbols
3	Simulation Iteration	200	Any number of iteration will do
4	Subcarrier Spacing (F)	15e3 (Hz)	LTE subcarrier spacing
5	Sampling Rate	$15e3*L*14$ (S/s)	considering to CP length of OFDM

ii. Design and Implementation of IFFT and FFT: Inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) performed at the transmitter and receiver to conversely convert the signal from time domain and frequency domain. The number of data samples $g_i(kK)$ injected to the IFFT input equals the number of multicarrier symbols, K. For a range $0 \le i \le K-1$, the resulting IFFT output signal $x[n]$ in the frequency domain was serialized by parallel-to-serial (P/S) converter and is given as follows [8]:

$$x(n) = \sum_{i=0}^{K-1} g_i(kK) e^{j2\pi \frac{i(n-kK)}{K}} \tag{2}$$

where k is the symbol index.

The IFFT and FFT were implemented in MATLAB R2018a, with the following set-up:

a. Sampling frequency of unity.
b. Carrier frequency spacing of $1/K$.
c. Multicarrier symbol period T which is $1/T_0$.

At the receiver end, a serial-to-parallel (S/P) converter parallelized the signal which was then retrieved from the output of the FFT as follows [8]:

$$g_i(kK) = \frac{1}{K} \sum_{n=kK}^{kK+K-1} x(n) e^{-j2\pi \frac{i(n-kK)}{K}} \tag{3}$$

iii. Filter Design and Implementation: The spectral superiority of FBMC is a function of proper design of filter and how they are applied to the subcarriers. PHYDYAS filter is a better choice owing to its energy concentration in time domain, rapid decaying in the frequency domain, reduced ICI, and flexibility with respect to overlapping factor, R. the overlapping factor determines the filter length L_p as shown in equation (4)[8]:

$$L_p = RK - 1 \tag{4}$$

where K is the number of subcarrier symbols.

The computation involved in the design and implementation of PHYDYAS filter is less compared to Hermit filter. This is because for PHYDYAS filter, the FFT and IFFT sizes of the system are not changed. The continuous frequency response $H(f)$ of the PHYDYAS filter is given in equation (5) and the impulse response $h(t)$ is obtained by taking the IFFT of $H(f)$ as presented in equation (6)[9]:

$$H(f) = \sum_{r=1-R}^{R-1} H_r \frac{\sin(\pi(\mathrm{f} - \frac{r}{RK})RK)}{RK\sin(\pi(\mathrm{f} - \frac{r}{RK})RK} \tag{5}$$

$$h(t) = 1 + 2\sum_{r=1}^{R-1} H_r \cos(2\pi \frac{rt}{RT}) \tag{6}$$

The filter was designed from equations (5) and (6) while the frequency impulse response of the filter as compared to Hermit filter is presented in Figure (2).

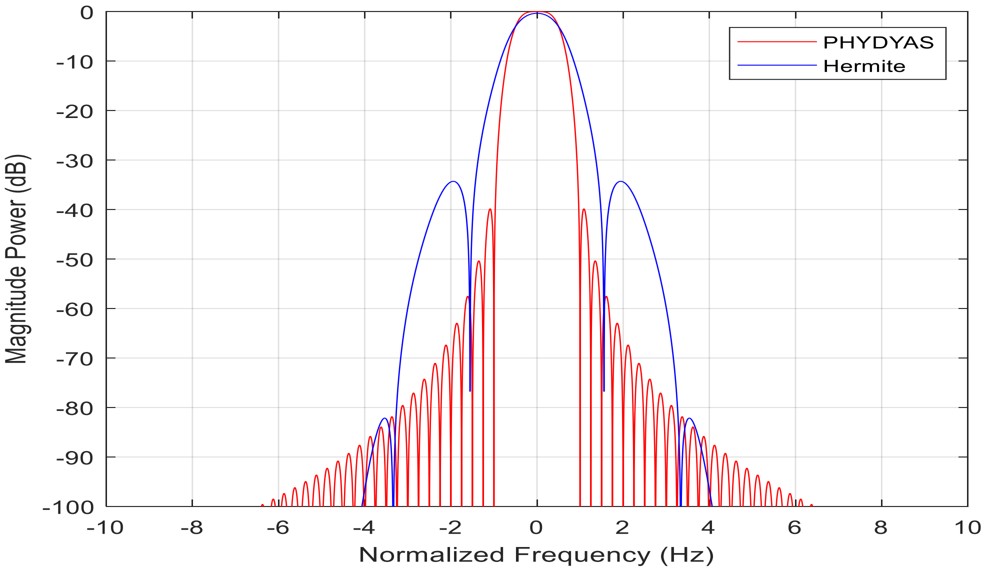

Figure 2: Frequency Impulse Response of PHYDYAS Filter as Compared to Hermit Filter.

iv. *OQAM Modulation of the FBMC Signal*

For the OQAM modulation of the FBMC signal, complex signal were generated and then successively transmitted between a half symbol delay. With the set-up parameters of Table 1, IFFT of size 1024 was implemented on the FBMC symbols of equation (2).

v. *Matrix Representation of the OQAM-modulated FBMC Data Symbols*

The OQAM-modulated FBMC data symbols are represented in matrix format to ease the computations involved. With the established set-up assumptions, the OQAM-modulated prototype pulse $p_{l,k}(t)$, and the complex transmit symbol $d_{l,k}$, at subcarrier position l and multicarrier position k of equation (2) were set as basis pulse vectors $\mathbf{p}_{l,k} \in \mathbb{C}^{N\times 1}$ and $\mathbf{d}_{l,k} \in \mathbb{C}^{LK\times 1}$. A pile of all the basis pulses is $\mathbf{P}_{l,k} \in \mathbb{C}^{N\times LK}$ transforms to the following:

$$\mathbf{P} = \left(p_{1,1} \quad \cdots \quad p_{\mathrm{n},1} \quad , \quad p_{1,lk} \quad \cdots \quad p_{n,lk} \right) \tag{7}$$

A stack of all the transmit symbols is $\mathbf{D}_{l,k} \in \mathbb{C}^{LK\times N}$ transforms as follows:

$$\mathbf{D} = \left(d_{1,1} \quad \cdots \quad d_{lk,1} \quad , \quad d_{1,\mathrm{n}} \quad \cdots \quad d_{lk,\mathrm{n}} \right) \tag{8}$$

The modulated transmit signal of equation (2) is now expressed in matrix notation as follows:

$$\mathbf{s} = \mathbf{P}\mathbf{D} \tag{9}$$

The received basis pulse $q_{l,\mathrm{k}}$ at subcarrier position l and multicarrier position k in a basis pulse vector is $\mathbf{q}_{l,k} \in \mathbb{C}^{N\times 1}$ and a pile of all the received basis pulses is $\mathbf{Q}_{l,k} \in \mathbb{C}^{N\times LK}$ which transforms into the following:

$$\mathbf{Q} = \left(q_{1,1} \quad \cdots \quad q_{lk,1} \quad , \quad q_{1,n} \quad \cdots \quad q_{lk,n} \right) \tag{10}$$

The sampled received signal $r(t)$ experiences a delay τ such that its impulse response h was modeled as time-variant convolution matrix $\mathbf{H} \in \mathbb{C}^{N\times N}$. The total received signal $r(t)$ when stacked as a vector signal is as follows:

$$\mathbf{r} = \mathbf{H}\mathbf{Q}\mathbf{D} \tag{11}$$

A stack of the received symbol In an additive white Gaussian (AWGN) channel where $\mathbf{P}$ equals $\mathbf{Q}$, and in the presence of Gaussian distributed noise but negligible channel induced interference, the received symbol is as follows:

$$\mathbf{y} = \mathbf{Q}^{H}\mathbf{H}\mathbf{P}\mathbf{D} + \mathbf{n} \tag{12}$$

where Q^H is the Hermitian of Q, whose conjugate of its complex entries is equal to the transpose of its complex conjugate, n is the Gaussian distributed noise.

A. Restoring orthogonality in imaginary domain by Hadamard coding scheme

Orthogonality in the imaginary domain of the complex matrix based data signal of equation (12) was restored by Hadamard coding scheme. In an additive white Gaussian noise channel, the impulse response of the system is an identity matrix as follows [10], thus equation (12) becomes:

$$\mathbf{y}=\mathbf{Q}^H\mathbf{P}\mathbf{D}+\mathbf{n} \tag{13}$$

The data symbols of equation (10) were pre-coded with a Hadamard matrix C as a pulse vector $C_{l,k} \in \square^{1\times LK}$ which was piled as equation (14), a stack of which transforms into equation (14):

$$\mathbf{C}=\begin{pmatrix} c_{1,1} & \cdots & c_{\mathrm{N},1} & , & c_{1,LK} & \cdots & c_{N,LK} \end{pmatrix} \tag{14}$$

$$\mathbf{D}=\mathbf{C}\mathbf{D}^{\mathbf{c}} \tag{15}$$

The received coded symbol $\mathbf{y}^c \in \square^{1\times LK}$ was obtained by projecting the stacked impulse response of the Hadamard matrix into the received symbols y, and with P equals Q in AWGN channel, the received coded symbol, y^c becomes the following:

$$\mathbf{y}^c=\mathbf{C}^H\mathbf{Q}^H\mathbf{Q}\mathbf{C}\mathbf{D}^c+\mathbf{n} \tag{16}$$

$\mathbf{C}^H\mathbf{Q}^H\mathbf{Q}\mathbf{C}$ forms an identity matrix of size LK, establishing orthogonality of the system.

II- Enhancing the Compatibility of MIMO with FBMC-OQAM System

The compatibility of the OQAM-modulated FBMC system with MIMO of 8 by 8 antennas was heightened. This was carried out as follows:

A. Cancellation of Imaginary Intrinsic Interference

Space-time transmission scheme was employed to cancel the imaginary intrinsic interference at the receiver end of MIMO of 8 by 8 antennas. For the transmission of 8 symbols, 4 time slots are needed[7]. The matrix representation of the STTS is as follows:

$$\mathbf{X}=\begin{pmatrix} x_1 & x_1 & -x_1 & \cdots & \pm x_1 \\ x_2 & x_2 & -x_2 & \cdots & \pm x_2 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ x_{N-1} & -x_{N-1} & x_{N-1} & \ddots & \mp x_{N-1} \\ x_N & -x_N & x_N & \cdots & \mp x_N \end{pmatrix} \tag{17}$$

where x_i is a complex symbol with $i \in \{1, 2, ..., 64\}$.

In the presence of Gaussian distributed noise, n, all over the channel, a stack of the noise $\mathbf{n}_{1\times N/2} \in \mathbb{C}^{1\times N/2}$ and channel coefficients $\mathbf{h}_{1\times N} \in \mathbb{C}^{1\times N}$ transform the received coded symbols into:

$$\mathbf{Y} = \mathbf{HX} + \mathbf{N} \qquad (18)$$

Y is a pile of received coded symbols, hence:

$$\mathbf{Y} = \begin{pmatrix} y_1 & y_2 & \cdots & y_{N/2} \end{pmatrix} \qquad (19)$$

Transmitting the Developed FBMC-OQAM Symbols over a MIMO System.

The coefficients of the received coded symbols of equation (19) are:

$$y_k = \sum_{i=1}^{k} h_i x_i - \sum_{i=k+1}^{N} h_i x_i + n_k \qquad (20)$$

where $k \in \{1, 2, ..., N/2\}$ with the highest entry of coefficient y_k as $N/2$. Thus, collecting the coefficients to obtain the following:

$$\frac{y_{i-1} + y_i}{2} = h_i x_i + w \qquad (21)$$

Thus, Y which is a stack of y_i for $i \in \{1, 2, ..., N/2\}$ transforms into the following:

$$\mathbf{Y} = 2\mathbf{H}\mathrm{x} + \mathbf{w} \qquad (22)$$

where w is Gaussian noise with zero mean and a unit variance.

III- Determining the Spectral Efficiency of the Developed System

The spectral efficiency of the developed 8 by 8 MIMO based OQAM-modulated FBMC system of equation (22) was determined using MATLAB with the setup parameters of table 2. Objectives I and II were repeated using Hermite filter where by Hadamard scheme was applied to equation (12) to redeem orthogonality in the complex domain. The term $\mathbf{C}^H\mathbf{Q}^H\mathbf{QC}$ of equation (16) is an identity matrix. A plot of the spectral efficiency of the systems against the number of subcarriers is presented in Figure (3).

Table 2: Setup Parameters for the Spectral Efficiency of the Developed System

S/N	Parameter	Numerical Value	Comment
1	Loop Subcarriers M_L	192	24 Subcarriers for each symbol
2	Symbols (K)	8	8 symbols for the 8 by 8 MIMO
3	Simulation Iteration	200	Any number of iteration will do
4	Complex Symbols	1	1 symbol per subcarrier
5	Subcarrier Spacing (F)	15e3 (Hz)	LTE subcarrier spacing
6	Number of FFT	1*1024	The FFT size
7	Sampling Rate	$15e3 * L * 14$ (S/s)	considering to CP length of OFDM

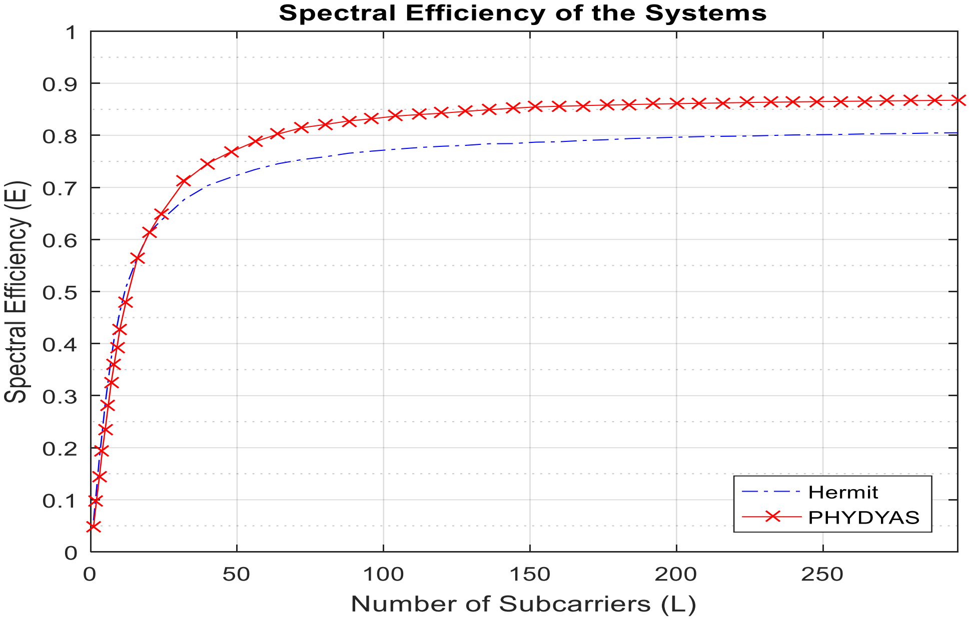

Figure 3: The Spectral Efficiency of the Systems.

Result and Discussion

From figure (3), the spectral efficiencies tend to be constant as at the subcarrier position for the 8 transmitted data symbols. The spectral efficiency of the PHYDYAS filter based system is 88% while that of the Hermit filter based system is 79%. This gives the former an increment of 9% efficiency over the latter. The efficiency of system developed using PHYDYAS filter as compared to Hermit filter is summarized in Table (3).

Table 3: Summary of the Result

Performance Metric	**PHYDYAS Filter**	**Hermit Filter**	**Percentage Increment**
Spectral Efficiency	88%	79%	9%

Conclusion

The primary difference of this research work with other established works is the antenna size and choice of filter for the OQAM-modulation of FBMC data symbols for transmission over a MIMO of 8 by 8 antennas. Some research work in addition to adopting a conventional MIMO of 2 y 2 antennas, have also used Hermit filter which is spectrally inferior compared to PHYDYAS filter. The filter adopted here is densely concentrated with energy in the time domain which gives it an edge to mitigating inter carrier interference. Thus, under the same conditions and setup parameters, the spectral efficiency of the PHYDYAS filter based system was significantly increased by 9% when compared to Hermit filter.

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