

Development of a Matrix-Based Bi-Orthogonal FBMC-OQAM Data Model Using Hadamard Scheme

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ABSTRACT

Filter Bank Multicarrier (FBMC) is an OFDM based multicarrier scheme that employs the use of prototype filter in place of cyclic prefix to nullify inter-carrier interference and inter symbol interference and is suitable for time and frequency localization. As a result, the spectral efficiency of FBMC is higher than other OFDM-based multicarrier techniques that use cyclic prefix. By modulating FBMC complex data symbols using offset quadrature amplitude modulation technique, capacity gain was improved but at the expense of disorienting the orthogonality of the imaginary components of the complex data symbols. This however, was corrected using Hadamard error correction coding scheme in order to obtain OQAM-modulated FBMC symbols which are orthogonal in both the real and imaginary field of the complex data symbols. The developed data symbols were represented in matrix format in order to simplify the computation involved.

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FFT, Filter-bank multicarrier, FBMC- OQAM, Hadamard scheme, IFFT, OOBE, MIMO, multicarrier modulation, PHYDYAS Filter, OFDM.

INTRODUCTION

There is a huge requirement for an effective data transmission in wireless communication systems in present times and in the future. To achieve that, there is need to optimally utilizing both the real and imaginary carrier components of a complex data symbols [1]. Filter Bank Multicarrier Offset Quadrature Amplitude Modulation (FBMC-OQAM) which is based on OFDM, offers higher data and is more spectrally efficient because of its little out of bound emissions (OOBE)[2]. The functionality rationale of FBMC-OQAM is in such a way that the modulation of the subcarriers is done at a shift (offset) of half the symbol period between the imaginary and real components of a complex QAM symbol [3]. Thus, OQAM modulating an FBMC complex data symbol improves the level of capacity gain without occupying additional radio spectrum in the frequency range[4], and it is

also robust to multipath fading [5]. This however come at the expense of disorienting orthogonality of the imaginary components[2]. The disoriented orthogonality can be set straight by employing Hadamard error correction coding scheme [6]. FMBC- OQAM is primarily similar to FBMC with Cosine-modulated Multi-Time (FBMC-CMT), FBMC with Staggered Multi-Time (FBMC-SMT) and FBMC with Pulse Amplitude Modulation (FBMC-PAM) due to their similar functionality [7]. With these superior advantages, OQAM modulated FBMC is applicable in the present wireless communication systems and beyond [8]. When transmitting OQAM-modulated data symbols over MIMO system, Imaginary intrinsic interference which is caused by the overlap of the filter response of two adjacent sub-channels is much [9]. Hadamard scheme in the process of restoring complex orthogonality in the imaginary domain, mitigates the effect

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of intrinsic imaginary interference by spreading symbols in time and frequency [10]. This research employed Hadamard technique in order to develop a matrix based bi orthogonal FBMC-OQAM data model.

MULTICARRIER MODULATION

Multicarrier modulation is a modulation technique whereby data signal is split into various parts with a view for transmission over distinct carrier signals of narrow bandwidth [11]. To some degree, multicarrier modulation is resistive of multipath fading, Inter-Symbol Interference

(ISI), and noise [11]. The model equation of a time continuous multicarrier signal [12] is as TON 8(2), JUNE, 2020
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$$
x(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} g_{l,k}(t) x_{l,k}
$$
 (1)

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(ISI), and noise [11]. The model equatio

time continuous multicarrier signal [12

follows:
 $x(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} g_{l,k}(t) x_{l,k}$ (1)

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and noise [11]. The model equation of a

continuous multicarrier signal [12] is as

s:
 $=\sum_{k=1}^{K}\sum_{l=1}^{L}g_{l,k}(t)x_{l,k}$ (1)

Among the key multicarrier

lation techniques, F Among the key multicarrier modulation techniques, FBMC-OQAM is more spectrally efficiency and has a better performance in terms of symbol density, time localization, frequency localization, and bi orthogonality as given in Table 1[9]

Table 1: Comparison of Different Multicarrier Modulation Techniques [9]

Multipath Propagation

In any wireless communication system, multipath propagation which is caused by atmospheric phenomena, is one in which a radio signal from a transmitter disperses and propagates via multiple channels in order to reach the transmitter[9]. The direct signal has the highest strength at the receiving antenna while the indirect signal have lesser strengths and their model equations are as follows [9]:

$$
x_D(t) = \cos(\hat{S}_0 t) \tag{2}
$$

$$
x_{R,N}(t) = \dots_{n} \cos(S_0 t - S_0 t)
$$
 (3)

any nth reflected (indirect) signal, $\boldsymbol{\check{S}}_0$ is angular frequency, $\;..._{n}$ is the differential amplitude, \ddagger is the differential time. Real only

Yes

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n is the differential amplitude, \ddagger

ttial time.

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The transmitter receives a summation of all the propagated signal components, y(t) [9]:

$$
y(t) = \sum_{n=0}^{N-1} \dots e^{jN_n} x(t - \dot{\mathbf{t}}_n)
$$
 (4)

where, e^{jW_n} is a complex exponential component of the amplitude.

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A. Offset Quadrature Amplitude Modulated Filter-Bank Multicarrier (FBMC-OQAM)

FBMC employs prototype filter to palliate inter-carrier interference and inter symbol interference. The prototype filter makes time and frequency localization easier and effective, hence giving FBMC higher

spectral efficiency. OQAM modulation of FBMC is in such a way that the modulation of the subcarriers is done at a shift (offset) of half the symbol period between the imaginary and real components of a complex QAM symbol [3]. The block diagram of FBMC-OQAM data symbol transceiver is shown in figure 1 [9]:

Figure 1: Block Diagram of FBMC-OQAM Transceiver[9].

The model equation of the transmit signal of OQAM-modulated FBMC is given [13] **1:** Block Diagron of the transform \mathbf{FBMC} is give
(5)
 (5)
 $\frac{12f\theta + \frac{1}{T}}{2\theta + \frac{1}{T}}$ (6)
OQAM-mod

$$
s(t) = \sum_{l=0}^{2L+1} \sum_{l=0}^{\infty} d_{l,k} p_{l,k}(t)
$$
 (5)

with,

$$
p_{1,k}(t) = j^{l+k} p(t - kT)^{2l} e^{j2f(t)^{-1}T} \qquad (6)
$$

Signal

Figure 1: Block Diagram of FBMC-OC

The model equation of the transmit

signal of OQAM-modulated FBMC is given [13]

as:
 $s(t) = \sum_{l=0}^{2L+1} \sum_{l=0}^{\infty} d_{l,k} p_{l,k}(t)$

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with,
 $p_{l,k}(t) = j^{l+k} p(t - kT/$ $s(t) = \sum_{l=0}^{2L+1} \sum_{l=0}^{\infty} d_{1k} p_{1k}(t)$ (5) except for a
with, orthogonal.
 $p_{1k}(t) = j^{l+k} p(t - kT/2) e^{j2f y \frac{1}{T}}$ (6) (size $n \times n$)
where, $p_{1k}(t)$ is the OQAM-modulated $HH^* = nI_n$
prototype pulse and d_{1k} is the com symbol at subcarrier index *l* and multicarrier index *k* .

HADAMARD SCHEME

scheme whereby the rows of a Hadamard matrix constitute the codewords [14]. Hadamard matrix is a square matrix which has only 1's and -1's arranged in such a way that each row of the matrix is different from other

Output

Signal

Figure 1: Block Diagram of FBMC-OQAM Transceiver [9].

The model equation of the transmit

of OQAM-modulated FBMC is given [13]

The model equation of the transmit

of OQAM-modulated FBMC is given [13]

Th rows in exactly $N/2$ places, making all the rows to have exactly $N/2$ 1's and $N/2$ -1's, except for a one of the rows that is composed of completely -1's [15]. In a Hadamard matrix, all the rows and columns are mutually orthogonal. Hadamard matrix *H* of *n* order [16]: From a book exactly $N/2$ places, finally all the
rows to have exactly $N/2$ 1's and $N/2$ -1's,
except for a one of the rows that is composed
all the rows and columns are mutually
orthogonal. Hadamard matrix H of n o

$$
HH^* = nI_n \tag{7}
$$

where I is an identity matrix of size n and H^{\dagger} **The Community of the Community** is the complex conjugate of *H* .

Hadamard coding scheme is a coding
correlation between codes. A simple 4×4 The length of the matrix (n) is analogous to the code length. Perfection of the orthogonality comes with the lack of cross Hadamard matrix is as follows [9]:

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(8)

JOURNAL OF SCIERICE TECHNOLOGY AND EDUCATION 8(2), JUNE, 22 ISSN: 2277-0011; Journal homepage: www.atbutfejoste.com		
$H_4 = \begin{pmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}$	1	1
H_5 General	1	1
DEVELOPMENT AND SIMULATION OF FBMC-	1	
2 QuadrADATA MODEL	2	3
2 QuadrADATA MODEL	4	
2 Considering a Paleich fading channel	5	

DEVELOPMENT AND SIMULATION OF FBMC- OQAM DATA MODEL

the multicarrier signal source of equation 4
was used to develop an FBMC-OQAM data reflected ray, $x_{R,N}(t)$ is trifling, and assuming was used to develop an FBMC-OQAM data model. The development was carried out in two steps, first by developing a matrix based FBMC-OQAM data system model and then employing Hadamard coding scheme to the $v = ... \cos(2f ft)$ data symbols in order to restore bi orthogonality.

Development of a Matrix Based FBMC/OQAM Data Model

FBMC/OQAM signal model was developed by constructing and modulating a multicarrier signal in a multipath Raleigh fading channel. The OQAM-modulated FBMC multipath signal was then transformed into a matrix notation by means of computation. It was so transformed into matrix in order to simplify the complex continuous-time multicarrier signal model. The step-by-step

operations for developing the matrix based FBMC-OQAM data model are as follows:

Generating and Simulating the Multipath Signal

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 $\begin{pmatrix} 1 & 1 & 1 \ 1 & -1 & -1 \ 1 & -1 & -1 \end{pmatrix}$ (8)

(a)

(a)
 Cenerating and Simulating the Multipath
 Ce JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

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FBMC-OQAM data model are as follows:
 $\begin{bmatrix}\$ Considering a Raleigh fading channel, between the direct ray, $x_D(t)$ and the nth The direct ray from a signal source of equation (2) and indirect rays of equation (3) in a multipath fading channel, sum up to give the model equation (4). If the differential time **DEDUCATION 8(2), JUNE, 2020**
 operations for developing the matrix based
 EBMC-OQAM data model are as follows:
 Generating and Simulating the Multipath
 Signal
 The direct ray from a signal source of
 equation D EDUCATION 8(2), JUNE, 2020

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operations for developing the matrix based

FBMC-OQAM data model are as follows:
 Generating and Simulating the Multipath
 Signal

The direct ray from a signal the phase shift of zero, the resultant signal of equation 2.3 will be modeled as the summation of the cosine function as follows: *y BEUCATION 8(2), UNNE, 2020

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 y **coreforms** *senerating and Simulating the Multipath***

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In some of developing the matrix based

DAM data model are as follows:
 tg and Simulating the Multipath

The direct ray from a signal source of

(2) and indirect rays of equation (3)

ipath fading cha

With the following arbitrary simulation set-up assumptions:

- a) 64 sample points of the multicarrier signal.
- b) Maximum propagation time, $=2e^{-3}$ seconds
- c) Minimum propagation time, $t_{\min} = 0$ seconds.
- d) Constant amplitude of one (1).

The received signal was constructed using equation 9 and plotted as presented in figure 2:

The multicarrier (FBMC) signal was modulated so as to transmit and receive offset QAM symbols, hence the FBMC-OQAM

symbols. The tasks carried out in the design of the FBMC signal model are as follows:

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OQAM Preprocessing

In designing the FBMC-OQAM signal model, complex multipath signal with real and imaginary components was preprocessed and sampled for the offset quadrature amplitude modulation. The sampling set-up parameters and their values are presented in Table 3.1.

IFFT and FFT Design and Implementation

Inverse fast Fourier transform (IFFT) and fast Fourier transform were performed at the transmitter and receiver to conversely
Multicarrier symbol period of $T = 1/T_0$. convert the multicarrier signal from time domain to frequency domain respectively. The number of data samples () *i g kK* injected to the IFFT input is equal to the number of multicarrier symbols, K . For a range **EXERCT:** HOWER THE SURVERT IN THE RESULTED STATE (10) EXERCT THE RESULTED (11) AND FORCOCKING THE RESULTED (11) AND FORCOCKING THE RESULTED (16) CONDET THE RESULTED (11) The resultion of the resultion of the resultion of *x n*[] in the frequency domain was serialized

by parallel-to-serial (P/S) converter and is given as follows [17]:

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\nby parallel-to-serial (P/S) converter and is given as follows [17]:

\n
$$
x(n) = \sum_{i=0}^{K-1} g_i(kK)e^{j2f\frac{i(n-kK)}{K}}
$$
 (10)

\nwhere k is the symbol index.

where k is the symbol index.

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/ parallel-to-serial (P/S) converter and is

ven as follows [17]:

(*n*) = $\sum_{i=0}^{K-1} g_i(kK)e^{j2f\frac{i(n-KK)}{K}}$ (10)

here k is the symbol index.

ne IFFT and FFT were im **D EDUCATION 8(2), JUNE, 2020**
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 y parallel-to-serial (P/S) converter and is

given as follows [17]:
 $x(n) = \sum_{i=0}^{K-1} g_i(kK)e^{j2f\frac{i(n-kK)}{K}}$ (10)

where k is the symbol index.

The IFFT and F The IFFT and FFT were implemented using the following set-up:

Sampling frequency of unity.

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by parallel-to-serial (P/S) converter and is

given as follows [17]:
 $x(n) = \sum_{i=0}^{K-1} g_i(kK)e^{i2f\frac{i(n-K)}{K}}$ (10)

where k is the symbol index.

The IFFT and FFT wer which was then retrieved from the output of the FFT as follows [17]: he symbol index.

1 FFT were implemented using the

t-up:

equency of unity.

1. experime of $1/K$.

symbol period of $T = 1/T_0$.

the receiver end, a serial-to-

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parallel-to-serial (P/S) converter and is

en as follows [17]:
 n) = $\sum_{i=0}^{K-1} g_i(kK)e^{i2f\frac{i(n-kK)}{K}}$ (10)

ere k is the symbol index.

EIFFT and FFT were implemented **FT** were implemented using the
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 complementary
 com F were implemented using the
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 *i*y spacing of $1/K$.
 hbol period of $T = 1/T_0$.
 receiver end, a serial-to-
 nverter parallelized the signal
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 ws [17]:
 $\sum_{n=k$ **g** B EDUCATION 8(2), JUNE, 2020
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 gy parallel-to-serial (P/S) converter and is

given as follows [17]:
 $x(n) = \sum_{i=0}^{K-1} g_i(kK)e^{i2\pi i(K-1/2)}$ (10)

where k is the symbol index.

The IFT and FF mbol index.

were implemented using the

ncy of unity.

spacing of $1/K$.

sol period of $T = 1/T_0$.

seceiver end, a serial-to-

verter parallelized the signal

etrieved from the output of

s [17]:
 $\frac{+K^{-1}}{K}x(n)e^{-j2f\frac{i(n$

$$
g_i(kK) = \frac{1}{K} \sum_{n=kK}^{kK+K-1} x(n)e^{-j2f} \frac{i(n-kK)}{K}
$$
\n(11)

inverse fast Fourier transform (IFFT) and fast Fourier transform were performed at the transmitter and receiver to conversely convert the multicarrier signal from time domain to frequency domain respectively. The number of data samples $g_i(kK)$ injected to the IFFT input is equal to the number of			Sampling incurrity of unity. Carrier frequency spacing of $1/K$. Multicarrier symbol period of $T=1/T_0$. At the receiver end, a serial-to- parallel (S/P) converter parallelized the signal which was then retrieved from the output of
multicarrier symbols, K . For a range			the FFT as follows [17]:
		$0 \le i \le K-1$ the resulting IFFT output signal $x[n]$ in the frequency domain was serialized	$g_i(kK) = \frac{1}{K} \sum_{n=k}^{kK+K-1} x(n)e^{-j2f \frac{i(n-kK)}{K}}$ (11)
		Table 3.1: The OQAM Preprocessing Setup Parameters.	
S/N	Parameter	Numerical Value	Comment
$\mathbf{1}$	Subcarriers (L)	24	Number of subcarriers for each symbol in FBMC
$\overline{2}$	Symbols (K)	64	Large number for better resolution. Precisely 64 in favor of Large MIMO
3	Simulation Iteration	200	Any number will do
4	Subcarrier Spacing (F)	15e3 (Hz)	LTE subcarrier spacing
5	Sampling Rate	$15e3 * L * 14$ (S/s)	Over sampled by 14 which correspond to CP length of OFDM to monitor OOB
Filter Design and Implementation The spectral superiority of FBMC comes with the proper design of filter and how they are applied to the subcarriers. The choice of the filter to be used was informed by the energy concentration in time domain, rapid decaying in the frequency domain to reduce Inter-carrier interference (ICI), and flexibility with respect to overlapping factor, R. the			overlapping factor determines the filter length L_p as shown in equation (3.4) [17]: $L_p = RK - 1$ (12) 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 which was

Table 3.1: The OQAM Preprocessing Setup Parameters.

Filter Design and Implementation

$$
L_p = K K - 1
$$

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used by authors such as [18]. This is because PHYDYAS filter maintains the FFT and IFFT sizes of the system.

The continuous frequency response **Hereafted is a filter of the PHYDYAS** filter is presented in the PHYDYAS filter maintains the FFT and IFFT sizes of the system.
The continuous frequency response $H(f)$ of the PHYDYAS filter is presented in equation (13) FORD MALL OF SCIENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

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used by authors such as [18]. This is because

PHYDYAS filter maintains the FFT and IFFT sizes

of t JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 8(2), JUNE,

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used by authors such as [18]. This is because

PHYDYAS filter maintains the FFT and IFFT sizes

of the syst is given in equation (14) [7] and were used in designing the filter:

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$$
H(f) = \sum_{r=1-R}^{R-1} H_r \frac{\sin(f(f - \frac{r}{RK})RK)}{RK \sin(f(f - \frac{r}{RK})RK)}
$$
(13)

$$
h(t) = 1 + 2 \sum_{r=1}^{R-1} H_r \cos(2f \frac{rt}{RT})
$$
(14)
The frequency impulse response of the filter is presented in Figure (3.4).

$$
h(t) = 1 + 2\sum_{r=1}^{N} H_r \cos(2f \frac{rt}{RT})
$$
\n(14)

The frequency impulse response of the filter is presented in Figure (3.4).

Figure 3: Frequency Impulse Response of PHYDYAS Filter.

A decaying trend could be seen in Figure (3) which is the basis for the filter choice. Parallel filters at the transmitter which made up the synthesis filter bank (SFB) at the filters are mapped with the analysis filter bank (AFB) at the receiver.

Matrix Representation of the Modulated Data Symbols.

In modulating the FBMC signal, the real and imaginary components of the complex signal were generated and then successively $P_{I,k} \in \square$ and $D_{I,k} \in \square$. A state of an transmitted between a half symbol delay. With the basis pulses is $P_{I,k} \in \square^{N \times LK}$ which transmitted between a half symbol delay. With the set-up parameters of Table 3, IFFT of size 1024 was implemented on the FBMC symbols of equation (7).

prototype pulse $p_{l,k}(t)$, and the complex
OQAM Modulation of the FBMC Signal and
Matrix Representation of the Modulated Data transmit symbol $d_{l,k}$, at subcarrier position l The reason for representing the OQAM-modulated FBMC data symbols in matrix format is to ease the computations involved by getting rid of unnecessary calculations. Maintaining the established set up assumptions, the OQAM-modulated **Proton Controllering Controllering (**)
 Proton Controllering () $\frac{2}{\sqrt{2}}$ **esponse of PHYDYAS Filter.**

The reason for representing the
 OQAM-modulated FBMC data symbols in

matrix format is to ease the computat Frequency (Hz)

esponse of PHYDYAS Filter.

The reason for representing the

OQAM-modulated FBMC data symbols in

matrix format is to ease the computations

involved by getting rid of unnecessary

calculations. Maintainin and multicarrier position *k* of equation (5) were written as basis pulse vectors $\mathcal{D}_{l,k} \in \Box^{N \times 1}$ and $D_{l,k} \in \Box^{LK \times 1}$. A stack of all Exports of PHTDTAS Filter.

The reason for representing the

DQAM-modulated FBMC data symbols in

matrix format is to ease the computations

molved by getting rid of unnecessary

calculations. Maintaining the established S FIREMC data symbols in

to ease the computations

ting rid of unnecessary

ttaining the established set-

the OQAM-modulated
 $P_{l,k}(t)$, and the complex
 $P_{l,k}$, at subcarrier position l

nosition k of equation (5) The reason for representing the

DQAM-modulated FBMC data symbols in

matrix format is to ease the computations

involved by getting rid of unnecessary

calculations. Maintaining the established set-

up assumptions, the transforms into the following:

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1,1 1, ,1 n, *lk n lk p p P p p* (15) , *LK N ^Dl k* which translates to the

$$
P = (p_{1,1} \cdots p_{n,1} , p_{1,k} \cdots p_{n,k}) \quad (16)
$$

A stack of all the transmit symbols is

following:

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\n
$$
P = \begin{pmatrix} P_{1.1} & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,k} \end{pmatrix}
$$

\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,k} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{1,k} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{1,k} & \cdots & P_{1,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,k} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,k} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,k} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,k} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,k} & \cdots & P_{n,k} \end{pmatrix}$
\n $P = \begin{pmatrix} 1 & \cdots &$

The modulated transmit signal of equation (5) is matrix format is now expressed as follows:

$$
s = P_D \tag{19}
$$

19)
 19) SEXAL ALTER (INSTERT SET (INSTERT)
 19) EXAL ALTER (INSTERT)
 19) EXAL ALTER (IS) 19) While a stack
 P $P = \begin{pmatrix} P_{1,1} & \cdots & P_{1,K} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,K} \end{pmatrix}$ **115) While a stack**
 P The received basis pulse q_{ik} at subcarrier position *l* and multicarrier position *k* in a basis pulse vector is $Q_{l,k} \in \Box^{N \times 1}$ and a stack of all the received basis pulses is $(D = \begin{pmatrix} d_{R,1} & \cdots & d_{R,n} \end{pmatrix}$
 $D = \begin{pmatrix} d_{1,1} & \cdots & d_{1,k,1} \end{pmatrix}$, $d_{1,n}$ $\cdots & d_{1,k,n}$ where n is the Gaussia
 $D = \begin{pmatrix} d_{1,1} & \cdots & d_{1,k,1} \end{pmatrix}$, $d_{1,n}$ $\cdots & d_{1,k,n}$
 $\cdots & d_{1,k,n}$
 $\cdots & d_{1,k,n}$
 $\cdots & d_{1,k,n}$
 $\cdots & d$ following: 1.1 $d_{k,n}$
 $d_{k,n}$
 $d_{k,n}$
 $d_{k,n}$
 $d_{k,n}$
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 $e^{ik\theta}$
 f and multicarrier position k in a stack of the section of *l* $d_{lk,1}$, $d_{1,n}$... $d_{lk,n}$ where n is the
 Restoring (Bi)
 lated transmit signal of equation (5)
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 g all the transmit symbols is
 $\begin{pmatrix}\nI_{K\times N} & \cdots & I_{K\times N} \\
I_{M\times N} & \cdots & I_{M\times n}\n\end{pmatrix}$
 $\begin{pmatrix}\nI_{11} & \cdots & I_{1n} \\
I_{21} & \cdots & I_{2n}\n\end{pmatrix}$
 $\begin{pmatrix}\nI_{22} & \cdots & I_{2n} \\
I_{33} & \cdots & I_{3n}\n\end{pmatrix}$
 $\begin{pmatrix}\nI_{12} & \cdots & I_{1n} \\
I_{23} & \cdots$ $d_{1,1}$... $d_{1,n}$... d_{1 Sowing:
 $\begin{bmatrix}\n\vdots & \vdots & \ddots & \vdots \\
\vdots & \ddots & \vdots \\
d_{n1} & \cdots & d_{1,n}\n\end{bmatrix}$ (17) Southern individed interference, the received
 $\begin{bmatrix}\n\vdots & \ddots & \vdots \\
\vdots & \ddots & \vdots\n\end{bmatrix}$ (17) Symbol is as follow *D* = $\begin{pmatrix} 1 & 1 & 1 \\ d_{R,1} & \cdots & d_{R,n} \end{pmatrix}$
 D = $\begin{pmatrix} d_{R,1} & \cdots & d_{R,n} \end{pmatrix}$
 D = $\begin{pmatrix} d_{11} & \cdots & d_{n,1} \end{pmatrix}$, $d_{1,a} & \cdots & d_{n,a} \end{pmatrix}$
 Restoring (Bi)-Orthogonolity by Hodomard
 Scheme
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$$
Q = \begin{pmatrix} q_{11} & \cdots & q_{1,n} \\ \vdots & \ddots & \vdots \\ q_{lk,1} & \cdots & q_{lk,n} \end{pmatrix}
$$
 (20)
g
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hddamard matrix C written as a pu

$$
C_{l,k} \in \sqcup^{1 \times LK}
$$
 which was stacked as f

 $(2\epsilon_{\rm R,1}$
 $\epsilon_{\rm R,2}$ at times and $D = \begin{pmatrix} d_{1,1} & \ldots & d_{ik,n} \end{pmatrix}$

(18)

Scheme

The modulated transmit signal of equation (5)

Scheme

The modulated transmit signal of equation (5)

sequation (25)

The received ba position v , met with a delay \ddagger such that its impulse response *h* was modeled as time- $Q_{l,k} \in \Box^{N\times LK}$ which transforms into the $y = Q^H P_D + n$
following:
following:
 $Q = \begin{pmatrix} q_{11} & \cdots & q_{1,n} \\ \vdots & \ddots & \vdots \\ q_{lk,1} & \cdots & q_{lk,n} \end{pmatrix}$ a Hadamard matrix C written as a pulse vector
 $Q_{lk,1} \cdots Q_{lk,n}$ (20) $C_{l,k} \in \Box^{k\t$ variant convolution matrix $H\in\Box^{N\times N}$. The The modulated transmit signal of equation (5)

is matrix format is now expressed as follows:
 $S = Pb$ (19)

The received basis pulse $q_{l,k}$ at subcarrier Assumir

position *l* and multicarrier position *k* in a channel

ba vector signal is as follows: In monoutate transmit signal or equation (1)
 S and this format is now expressed as follows:
 S and thus consisting an additive white
 R B D L (19) equation (2) to restore the modulated transming an additive w

$$
r = HQD \tag{22}
$$

While a stack of the received symbols is thus:

$$
v = Q^{n} r \tag{23}
$$

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

ISSN: 2277-0011; Journal homepage: www.atbuftejoste.com
 $\begin{pmatrix}\nP_{1,1} & \cdots & P_{1,k} \\
\vdots & \ddots & \vdots \\
P_{n,1} & \cdots & P_{n,k}\n\end{pmatrix}$ (15)

While a stack of the received symbo JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

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 $\begin{pmatrix}\nP_{1,1} & \cdots & P_{1,k} \\
\vdots & \ddots & \vdots \\
P_{n,1} & \cdots & P_{n,k}\n\end{pmatrix}$ (15)

While a stack of the received symbo JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

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11.1 ... $P_{1..k}$
 \vdots ... \vdots ... (15)
 \vdots ... (15)
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 \vdots ... $P_{n,1}$... P *Helmon S(2), JUNE, 2020*
 Helmon S(2), JUNE, 2020
 Helmon Stack of the received symbols is thus:
 Helmon G(2)
 Where Q^H *is the Hermitian of* Q *, whose*
 Mere Q^H *is the Hermitian of* Q *, whose*
 Mergon Stac where Q^H is the Hermitian of Q , whose conjugate of its complex entries is equal to the transpose of its complex conjugate.

$$
y = Q^H H Q D \tag{24}
$$

100RNAL OF SCENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

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 $P = \begin{pmatrix} P_{1,1} & \cdots & P_{1,k} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,k} \end{pmatrix}$ (15)
 $P_{m,1}^{(1,1)}$ (15)
 $P_{m,1}^{(2,1)}$ *H D* EDUCATION 8(2), JUNE, 2020
 H y = *Q* ^{*H*} *<i>y* = *Q*^{*H*} *r* (23)
 *While a stack of the received symbols is thus:

<i>y* = *Q*^{*H*} *is* the Hermitian of *Q*, whose

conjugate of its complex entries is equ In an additive white Gaussian (AWGN) channel where P equals Q , and in the presence of Gaussian distributed noise but negligible channel induced interference, the received **HET** *HET ET ET ET P <i>MERERT ALTON SCELUS (STERT THE SCELUS 100 (STERT 100)

<i>HET P* μ *HET* Q^H *is the Hermitian of* Q *, whose* **onjugate of its complex entries is equal to the ranspose of its complex**

$$
y = Q^{n} H P_{D+n}
$$
 (25)

where n is the Gaussian distributed noise.

Restoring (Bi)-Orthogonality by Hadamard Scheme

(17) symbol is as follows:
 $y = Q^H H P_D + n$ (25)
 $d_{1,n}$ $d_{1,n}$ $d_{lk,n}$

Restoring (Bi)-Orthogonality by Hadamard

sit signal of equation (5)

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equation (25)

wexpressed as follows:

(19)

equation (1₁ ... P_{R1} , P_{R2} is the term and the present of the term and the stress of the present of the stress of the stress of d_{11} ... d_{1n} . where Q^N is the Hermitian of Q , whose
 $\therefore P_{a,b}$ $P_{a,b}$ (15) compages of its complex conjugate.
 $\therefore P_{a,b}$ (16) termspose of its complex conjugate.

all the transmit symbols is $y = Q^N HQ_0$.
 \therefore $d_{a,b}$ $y = Q^N HQ$ Hadamard coding scheme was employed to the modulated transmit signal of equation (25) to restore the complex orthogonality of the FBMC-OQAM system. Assuming an additive white Gaussian noise channel, the impulse response of the system is an identity matrix as follows: where Q^H is the Hermitian of Q , whose
conjugate of its complex entries is equal to the
ranspose of its complex conjugate.
 $y = Q^H H Q D$ (24)
n an additive white Gaussian (AWGN) channel
where P equals Q , and in the p *Here* \sum *B is let Herminal on the*
 Here \sum *M Herminal on the transpose of its complex conjugate.* (24)
 A an and ditive white Gaussian (AWGN) channel
 Here P equals Q , and in the presence of
 He employed to the modulated transmit signal of
equation (25) to restore the complex
orthogonality of the FBMC-OQAM system.
Assuming an additive white Gaussian noise
channel, the impulse response of the system is
an identity mality of the FBMC-OQAM system.

g an additive white Gaussian noise

the impulse response of the system is

tity matrix as follows:

(26)

(25) thus becomes the following:

(26)

(25) thus becomes the following:

(27)

Th *c* induced interference, the received

is as follows:
 $\int_{\mu}^{\mu} H P_{D+R}$ (25)

is the Gaussian distributed noise.
 cg (*Bi*)-*Orthogonality by Hadamard*

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Hadamard coding scheme was

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 c \overline{L} is the Gaussian distributed noise.
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noho is as follows:
 $= Q^H H P_0 \cdot n$ (25)
 $= Q^H H P_0 \cdot n$ (25)
 $= P^H$ is the Gaussian distributed noise.
 \cdots Headamard coding scheme was
 $Q^H H P_{\nu}$ + n

en is the Gaussian distributed noise.

ring (Bi)-Orthogonality by Hadamard

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 Restoring (Bi)-Orthogonality by Hadamard

Hadamard coding scheme was

Hadamard coding scheme was

equation (25) to restor the complex

orthogonality of the FBMC-OQAM system.

Assuming an additive white Gaussian noise

t

$$
H = I_n \tag{26}
$$

Equation (25) thus becomes the following:

$$
y = QH PD + n
$$
 (27)

The complex valued transmit-data symbols of equation (18) were pre-coded with a Hadamard matrix C written as a pulse vector

$$
H = I_n
$$
 (26)
Equation (25) thus becomes the following:

$$
y = Q^H P D + n
$$
 (27)
The complex valued transmit-data
symbols of equation (18) were pre-coded with
a Hadamard matrix C written as a pulse vector

$$
C_{l,k} \in \sqcup^{1 \times LK}
$$
 which was stacked as follows:

$$
C = \begin{pmatrix} c_{1,1} & \cdots & c_{1,LK} \\ \vdots & \ddots & \vdots \\ c_{N,1} & \cdots & c_{N,LK} \end{pmatrix}
$$

(28)

$$
C = \begin{pmatrix} c_{1,1} & \cdots & c_{1,LK} \\ \vdots & \ddots & \vdots \\ c_{N,1} & \cdots & c_{N,LK} \end{pmatrix}
$$

(29)

$$
C = (c_{1,1} \quad \dots \quad c_{N,1} \quad , \quad c_{1,LK} \quad \dots \quad c_{N,LK})
$$
\n(29)

The stack of the coded complex transmit symbols D of equation (25) is translated to the following:

(3.14)

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The received coded symbol $y^{c} \in \Box^{1 \times LK}$ was obtained by projecting the stacked impulse response of the Hadamard matrix into the received symbols y as follows: *c H y C y* **FOR A FOREX A FOREX A PERIMBED ISSN:** 2277-0011; Journal homepage: www.atbuftejoste.com

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D = Cb^c
 $D = Cb^c$
 $y^c = C_3^H \frac{D^H}{Q^C b^c}$

The terms of the Hadamard

$$
y^{c} = C^{n} y
$$

$$
y^{c} = C^{H} Q^{H} P_{D+n}
$$

$$
y^{c} = C^{H} O^{H} P C_{D}^{c}
$$

With P equals Q in AWGN channel, the

received coded symbol, y^c , becomes the following:

$$
y^{c} = Q_{30}^{H} Q^{H} Q C D^{c} + n \qquad (34)
$$

**Following the SCENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

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** *D* **=** C_D^c **
** $y^c = C_B^H Q^H Q C_D^c + n$ **(34)

The received coded symbol** $y^c \in U^{bL/K}$ **was

bothered the** The terms $C^H Q^H Q C$ constitute an $\begin{pmatrix} 31 \\ 1 \end{pmatrix}$ protang a diagonally proton in $\begin{pmatrix} 31 \\ 2 \end{pmatrix}$ position₍ $\mathfrak{B} \mskip-5mu\int$ the complex data symbols which **Example 10**

IOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 8(2), JUNE, 2020

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 D = C_D^c
 c $y^c = G_{30}^H Q^H Q C_D^c * n$

The received coded symbol $y^c \in L^{1 \times LK}$ was decritains orthogonality of the data symbols.
The orthogonality plot is given in Figure 4. *c H H c y C Q QC D n* The terms $C^H Q^H Q C D^c + n$ (34)

The terms $C^H Q^H Q C$ constitute an

matrix of size LK which establishes the

matrix of size LK which establishes the

hality of the system as given in

(8) [16]. The orthogonality was

gay identity matrix of size LK which establishes the orthogonality of the system as given in equation (8) [16]. The orthogonality was checked by plotting a diagonally plot of the ascertains orthogonality of the data symbols.

The congestion coupled with underutilization of the available radio spectrum in the sub-six Giga Hertz scarcity of $\frac{1}{1}$ radio spectrum in wireless communication necessitates the need for spectral and bandwidth channel efficient schemes that will ensure the optimal utilization, especially in the next generation wireless communications systems. By employing Hadamard coding scheme on OQAM-modulated FBMC,
orthogonality in its imaginary field was [2] orthogonality in its imaginary field was restored to have bi-orthogonal carrier signals. As such, assuming zero channel impairments,

the spectral efficiency and bandwidth channel capacity was doubled.

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