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Out of Band Reduction on Advanced Modulation for MIMO Radar

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Abstract: This paper presents a system concept of an advanced modulation for Multiple Input Multiple Output (MIMO) radar. Multi-carrier modulation should be used for having efficient bandwidth. In this article, we proposed the modulation used on 5G specially to reduce MIMO radar Out of Band (OOB), to avoid the doppler effect and to beam the wave at a specific angle. The first proposition is the MIMO radar with Orthogonal Frequency Division Multiplex (OFDM) modulation, which uses Inverse Fast Fourier Transform (IFFT) to separate sub-carriers. In the spectrum analyzer, two domains appear: the In Of Band (IOB) for the spectrum efficiency and the Out Of Band (OOB) for not interfering with other frequencies. This article proposes the advanced modulation combined with MIMO Radar. So, the OFDM could be used. For improvement, the Universal Filtered Multi-Carrier (UFMC) and Filter Bank Multi-Carrier (FBMC) are used. Instead of filter for all band, the UFMC replace filter for each sub-band and the FBMC for each sub-carrier. To improve this OOB reduction on MIMO Radar UFMC, the subdivision of using multiple IFFT permits us to filter this sub-group of IFFT separately and efficiently. The last proposition concerns the MIMO Radar FBMC. In this proposition, all sub-carriers of IFFT used a new filter named PHYsical layer for DYnamic spectrum AccesS (PHYDIAS) which is different from the rectangular filter for the UFMC and OFDM. All theories of the 3 techniques used will be studied in this article. The simulation, result and discussion are released on Matrix Laboratory (MATLAB). The FBMC offers a very small OOB and big IOB, but his inconvenient concerns a complex digital processing indeed on the filter. The UFMC has an acceptable OOB, IOB and digital processing.

Keywords: OFDM, UFMC, FBMC, MIMO, RADAR

1. Introduction on MIMO radar

A MIMO radar could be a system collocated with N_t antenna's emitter and N_r antenna's receiver. It transmits some discrete time wave noted $\mathrm{S_m} \in \mathbb{C}^{\mathrm{L}}$. Let $\mathrm{S} = [\mathrm{s_1}, \mathrm{s_2}, \dots, \mathrm{s_{N_t}}]^{\mathrm{T}} \in \mathbb{C}^{N_t \times L}$, the matrix of emitter waves where L will be the wavelength. Knowing that, the radar emits M impulsions in the interval of coherent treatment with the frequency f_r [1-5].

1.1. Target's Signal

After having the signal to the emitter, the target sends this another signal expressed by the equation (1):

$$\mathrm{Y_{t,m}} = \beta_{\mathrm{t}}.\exp^{\mathrm{j(m-1)\omega_t}} \mathrm{a_r}(\theta_{\mathrm{t}}) \mathrm{a_t^T}(\theta_{\mathrm{t}}) \mathrm{s} \quad (1)$$

Where,

$a_t(\theta_t) = [\,1, \dots, e^{j(N_t-1)\pi d_t sin\theta_t}]^T$: antenna emitter's vector director;

$a_r(\theta_t) = [\,1, \dots, e^{j(N_r-1)\pi d_r sin\theta_t}]^T$: antenna receiver's vector director;

θ_t: the arrival's direction of target;

β_t: the amplitude of signal;

$\omega_{\mathrm{t}} = 2\pi \mathrm{f_t}, \mathrm{f_t}$: the doppler frequency of a normalized target.

1.2. Mathematics of Received Signal

The number of emitter antenna will be noted by n_T and receiver antenna will be N_r. Three (03) components should be studied for having more efficient models:

1) A propagation channel between target and the RADAR MIMO.
2) A reflective target.
3) A channel reverses to the receiving probe.

The emitter and receiver will be parameterized with γ.

So, the random process is the approximative model to join the emitter and receiver for having the target response. The equation (2) represents the received signal.

$$y = \begin{bmatrix} S(\gamma,1) & 0\cdots & 0 \\ 0 & S(\gamma,2) \; \dots\dots & \vdots \\ . & . & \\ 0 & 0\cdots & S(\gamma,n_R) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ . \\ a_{n_R} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ . \\ n_{n_R} \end{bmatrix} \quad (2)$$

Let $e_k(t)$ the respective impulse response of k different target.

$$e_k(t) = \sum_{rf=1}^{R_f} m_{r_f}^{(k)} \delta\left(t - \tau_{r_f}^{(k)}\right) \quad (3)$$

Where,

$m_{r_f}^{(k)}$ and $\tau_{r_f}^{(k)}$: the magnitudes of the response for each repair center r_f and the time delay.

The transmitted waveforms $o_i(t)$ are also normalized to unity energy with energy levels defined by p_i for all $i \in [1,\cdots,T]$. Each waveform is multiplied by a beamforming vector $u_i \in \mathbb{C}^{N_T X1}$ to focus on the transmitted waveforms on the radar scene.

Thus, the transmitted radar MIMO signal represents a linear combination of the totality of all beams of the transmitted and associated waves at similar energy levels. It will be expressed by the equation (4).

$$o(t) = \sum_{i=1}^{T} u_i s_i \sqrt{p_i} \quad (4)$$

Losses or pathloss in free space are expressed by $l_T^{(k)}$ and $l_R^{(k)}$ for transmitting and receiving paths relating to each k individual target of the respective radar. Since each target is at the azimuth angle $\mathfrak{h}_K$ relative to the transmission row, the reflected signal of the k-th target can be defined as:

$$y_k(t) = e_k(t) * \left[\beta_T^H(\mathfrak{h}_k) o(t) l_T^{(k)}\right], k = 1, \dots, K, \quad (5)$$

Where,

$\beta_T(\mathfrak{h}_K) \in \mathbb{C}^{N_T X1}$: vector of various ranges in the direction of the target;

(*): the convolution operator;

$(.)^H$: Hermitian or the complex transpose operator.

When the reflected signal is received by the RADAR MIMO receiver, the received signal is expressed as the equation (6):

$$z_r(t) = \sum_{k=1}^{K} \sum_{i=1}^{T} \alpha_{ri}^{(k)} [e_k(t) * o_i(t)] \sqrt{p_i} + \sum_{e=1}^{C_s} \sum_{i=1}^{T} \mu_{ri}^{(e)} [e_e(t) * o_i(t)] \sqrt{p_i} + v_r^H \eta(t) \quad (6)$$

Where,

$\beta_R(\theta_k) \in \mathbb{C}^{N_R X1}$: the vector director of various ranges of reception antenna of the azimuth direction;

$\theta_k, \alpha_{ri}^{(k)} = l_R^{(k)} v_r^H \beta_R(\theta_k) \beta_T^H(\mathfrak{h}_k) y_k l_T^{(k)}$: reflexion coefficient;

$e = 1, \dots, c_s$: source of clutter;

The coefficients of periodic reflection and complexes of "clutter" $\mu_{ri}^{(e)}$ defined by $\alpha_{ri}^{(k)}$ for the target radar with $\mu_{ri}^{(e)} = \tilde{l}_R^{(k)} v_r^H \tilde{\beta}_R(\tilde{\theta}_e) \beta_T^H(\tilde{\mathfrak{h}}_e) y_k \tilde{l}_T^{(k)}$. Note that, $\mu_{ri}^{(e)}, \tilde{l}_R^{(k)}$ and $\tilde{l}_T^{(k)}$ define the pathloss coefficients corresponding to each source and "clutter" for the transmission and receiving paths, respectively.

The coefficient $\tilde{\mathfrak{h}}_e$ and $\tilde{\theta}_e$ indicates the azimuths at which each source of "clutter" is produced relative to the transmission and receiving ranges, respectively.

1.3. New Mathematics of Received Signal

In this theory, the model uses Uniform Linear Antenna (ULA) for having a specific beam in a specific angular.

The signal to be transmitted is defined by the equation (7):

$$x(m) = [x_1(m)\; x_2(m) \dots .\, x_{n_T}(m)] \quad (7)$$

$x_n(m)$: the baseband signal of the m-ith emission element at the time index m.

The target has some specific emplacement named by θ_k This received signal could be expressed by:

$$r_k(m) = \sum_{n=1}^{n_T} e^{-j(n-1)\pi \sin\theta_k} x_n(m), \text{with}, k = 1,2, \dots K \quad (8)$$

$$r_k(m) = a^H(\theta_k) x(m) \quad (9)$$

Where: $a(\theta_k)$ is the vector director defined by:

$$a(\theta_k) = [\, 1\; e^{j\pi \sin\theta_k}\; e^{j2\pi \sin\theta_k} \dots\dots .\, e^{j(n_T-1)\pi \sin\theta_k}] \quad (10)$$

2. Advanced Waveform Modulation

2.1. Advanced Modulation

The sub-carries transmit parallel symbol and divided for all bandwidth for OFDM methods. So, we could have high rate of data using these methods. The Figure 1 on the top shows this OFDM filter. An OFDM signal is the sum of all sub-carrier's signal which are transmitted at each sub channels [5-16].

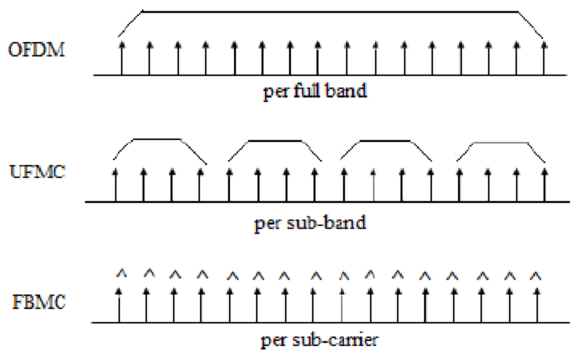

Figure 1. *Location of filtering for each modulation methods (OFDM – UFMC – FBMC).*

Out of Band (OOB) on spectrum should be reduced by using new transformations and adding new filter. On UFMC, filtering is located per each sub-band and on FBMC, it will be located per each sub-carrier.

2.2. Offset of Quadrature Amplitude Modulation (OQAM) on Advanced Modulation

The techniques of OQAM could be composed with 2 processes [6]:

1) On the emitter, the OQAM preprocessing.
2) On the receiver, the OQAM postprocessing.

Firstly, in the pre-processing block, the complex/real conversion will be used. Indeed, instead of sending complex symbols like on QAM symbols.

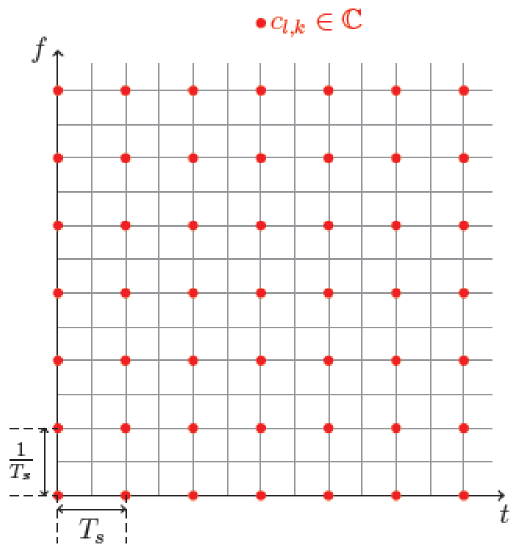

Figure 2. *QAM and time latency.*

The latency between the two modulation QAM and OQAM could be found on the Figures 2 and 3. In this, the constant k is the temporal index and l for the frequency index.

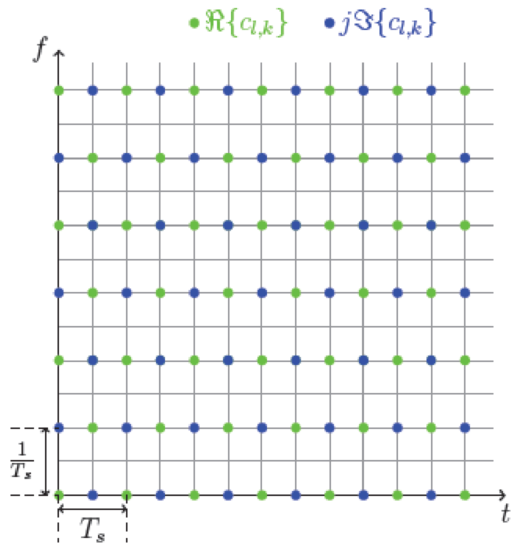

Figure 3. *OQAM and time latency.*

The principle of OQAM could be explained as:

1) Two symbols on the same carrier must be successively real and purely imaginary.
2) In addition, the adjacent symbols between the two under carrier must also be successively real and purely imaginary.

The real symbols $a_{l,k}$ will be transformed to a complex OQAM symbols named $C_{l,k}$ as expressed as on the equation (11). Like k represents the temporal index and l the frequent index.

$$a_{l,k} = \begin{cases} \mathrm{Real}(C_{l,k}) \text{ si l pair et k pair} \\ \mathrm{Imag}(C_{l,k}) \text{ si l impair et k pair} \\ \mathrm{Imag}(C_{l,k}) \text{ si l pair et k impair} \\ \mathrm{Real}(C_{l,k}) \text{ si l impair et k impair} \end{cases} \quad (11)$$

The next methods about OQAM pre-processing conceerns the multiplication by the imaginary part.

$$\theta_{l,k} = j^{l+k}.$$

The final symbols of OQAM pre-processing will be expressed like on the equation (12) and it will be note like $X_{l,k}$:

$$X_{l,k}(t) = \sum_{k=-\infty}^{+\infty} \theta_{l,k}.a_{l,k}.\delta(t - k\tfrac{T_s}{2}) \quad (12)$$

Where,

$\delta(t)$: impulsion of Dirac

The OQAM post-processing has: a multiplication by $\theta^*{}_{l,k}$ noted by the conjugate complex of $\theta_{l,k}$. Then, it is possible to convert the real into complex form. Indeed, two real symbols successively on a carrier form a complex symbol. The complex symbols on the carrier l using OQAM post-processing will be expressed on the equation (13).

$$C_{l,k} = \begin{cases} a_{l,k} + a_{l,k+1} \text{ if l even and k even} \\ a_{l,k+1} + a_{l,k} \text{ if l odd and k even} \\ a_{l,k-1} + a_{l,k} \text{ if l even and k odd} \\ a_{l,k} + a_{l,k-1} \text{ if l odd and k odd} \end{cases} \quad (13)$$

2.3. MIMO Radar with OFDM-OQAM

The system MIMO radar has M transmitter antennas and N receiver antennas. The transmitters are placed parallel to the axis of the abscesses. Each antennas will be spaced with distance d_t. The equation (14) expressed the coordination of the antenna:

$$E_m = E_0 + m.d_t.x. \quad (14)$$

Where, m= 0,…, M-1 and $E_0 = [x_{t,0}, y_{t,0}, z_{t,0}]^T$

The first transmitter is located in the center O (0,0,0) and et $x = [1,0,0]^T$ is the unitary vector on the axis of x.

The receiver antenna will be placed as same as the transmitter antenna and spaced with distance. The equation (15) expresses the coordinate of n-ith receiver antenna

$$R_n = R_0 + n.d_r.y, \quad (15)$$

Where, $R_0 = [x_{r,0}, y_{r,0}, z_{r,0}]^T$ and $y = [0,1,0]^T$

The OFDM modulation [7-10] is a transmission system having an initial carrier frequency f_0. The base band OFDM signal consists of N sub-carrier frequencies with a uniformly spaced frequency Δf. The equation (16) express all bandwith on OFDM.

$$B\omega = N.\Delta f \tag{16}$$

The n-ith sub-carrier is modulated with a K-ith code sequence. The OFDM should respect the condition of orthogonal waveform. For this, the equation (17) should be respected.

$$c_{n,p} = [b_{n,p}^{(0)}, \dots, b_{n,p}^{(K-1)}]^T \tag{17}$$

Where, $c_{n,p}^H c_{n,p} = \begin{cases} 1, p = p' \\ 0, p \neq p' \end{cases}$

So, $c_n = [c_{n,0}, \dots, c_{n,P-1}] \in C^{K\times P}$

The symbol c_n could be expressed on matrix form like:

$$c_n^H c_n = I_n$$

For having orthogonality, this formula should be respected:

$$t_b.\Delta f = 1$$

Where, t_b represents the bit length

The equation (18) represents the m-ith impulsion for the OFDM:

$$u_m(t) = \sum_{n=0}^{N-1}\sum_{k=0}^{K-1} b_{n,m}^{(k)} \exp^{\{j2\pi t\Delta f(t-(k+1))t_c\}} rect(\frac{t-kt_s}{t_s} - \frac{1}{2}) \tag{18}$$

With,

$t_s = t_b - t_c$: symbol duration

$t_c = \propto t_b$: cyclic prefix duration

m = 0,…, P-1

$rect(t) = \begin{cases} 1, \frac{-1}{2} \leq t < \frac{1}{2} \\ 0, others \end{cases}$: rectangular signal

At the beginning, the initial carrier frequency f_0 permits to transmits a baseband signal $u_m(t)$.

A target set is composed of the scattered ideal points I. The coordinate of i-th dispersed point is expressed by the equation (19):

$$D_i = [x_i, y_i, z_t]^T \tag{19}$$

The amplitude concerning the relative dispersion noted by σ_i is a constant within an OFDM pulse width and for multiple transmitter/receiver channels.

The target velocity is fully estimated and compensated after pre-processing. The Doppler effect is negligible in all echo models as expressed by the equation (20):

$$t = \tau_{min} + kt_s + t_c + t_0, \tag{20}$$

With,

τ_{min}: the beginning of a sample;

$t_0 \in [0, t_b]$: initial time.

The time interval of a p-th transmit and q-th receiver and i-th scatter is expressed by the equation (21).

$$\tau_{p,q}^{(i)} = \frac{(\|D_i - t_p\| + \|R_q - S_i\|)}{C} - \tau_{min} \tag{21}$$

Where,

c: the speed of light.

After the downlink, the equation (22) expresses the echo.

$$s_q^{(k)}(t_0) = \sum_{p=0}^{P-1}\sum_{i=1}^{I} \sigma_i \exp^{(-j2\pi f_0 \tau_{p,q}^{(i)}} \sum_{n=0}^{N-1} \exp^{\{i2\pi\Delta f(t_0 - \tau_{p,q}^{(i)}\}} \sum_{k'=0}^{K-1} b_{n,p}^{(k')} \, rect\left(\frac{(k-k')t_s + t_c + t_0 - \tau_{p,q}^{(i)}}{t_s} - \frac{1}{2}\right) + \vartheta_q^{(k)}(t_0) \tag{22}$$

Where,

$\vartheta_q^{(k)}(t_0)$: the noise,

and $rect\left(\frac{(k-k')t_s + t_c + t_0 - \tau_{p,q}^{(i)}}{t_s} - \frac{1}{2}\right) = \delta(k - k')$; $\delta(.)$ is an impulse function.

For the following, the processing methods will be described.

For q-th element received, and for k-th OFDM bit, the DFT calculation follows the sample index at a fast time. The echo in a frequency domain is expressed by the equation (23).

$$x_{n,q}^{(k)} = \frac{1}{N}\sum_{n=0}^{N-1} \exp^{\left(j2\pi\frac{nl}{N}\right)} s_{lq}^{(k)} = \sum_{i=0}^{I} \sigma_i \exp^{\{-j2\pi(n\Delta f + f_0)\tau_{p,q}^{(i)}\}} \sum_{p=0}^{P-1} b_{n,p}^{(k)} + V_{lq}^{(k)} \tag{23}$$

Where,

$x_{n,q}^{(k)}$: the n-th point results of the DFT and the echo in a frequency domain with n-th subcarrier.

$V_{lq}^{(k)}$: the noise.

N sub-carriers are separated without inter-carrier interference but the echoes received in P transmitting antennas are multiplexed and named serial to parallel.

The K bits DFT result should be represented by a column vector to separate the transmitter and decode the sub-carriers

$$s_{n,q} = [S_{n,q}^{(0)}, \dots, S_{n,q}^{(K-1)}]^T \tag{24}$$

Let,

$$s_{n,q} = C_n E_{n,q} \sigma + v_{n,q} \in \mathbb{C}^{K\times 1} \tag{25}$$

Where,

$C_n \in \mathbb{C}^{K\times P}$ and $E_{n,q}$: complex matrix with dimension $P \times I$;

$\varepsilon_{n,p,q}^{(i)} = \exp^{\{-j2\pi(n\Delta f + f_0)\tau_{p,q}^{(i)}\}}$: element of matrix C_n and the response of i-th disperser to n-th subcarrier for (p,q)-the transmitter/receiver chain;

$\sigma = [\sigma_1, \dots, \sigma_i]^T$: dispersion coefficient ;

$v_{n,q} = [V_{n,q}^{(0)}, \dots, V_{n,q}^{(K-1)}]^T \in \mathbb{C}^{K\times 1}$: vector noise.

Let,

$$R_{n,,q} = [r_{n,0,q}, \ldots, r_{n,P-1,q}]^T \in \mathbb{C}^{K\times 1} \quad (26)$$

$$R_{n,q} = C_n^H x_{n,q} = E_{n,q}\sigma + v'_{n,q} \quad (27)$$

Where,

$r_{n,p,,q}$: Modulated echo;

$v'_{n,q}$: Noise vectors modified without power change,

For each OFDM subcarrier, each transmitter/receiver pair:

$$\varepsilon_{n,p,q}^{(0)} = exp^{\{j2\pi(n\Delta f+f_0)\tau_{p,q}^{(0)}\}},$$

$$\tau_{p,q}^{(0)} = \frac{\|o-Z_p\|\|W_q-o\|}{c} - \tau_{min} \quad (28)$$

$r_{n,p,q}$ is multiplied by $\varepsilon_{n,p,q}^{(0)}$ for a compensated initial phase.

$$h_{n,p,q} = \varepsilon_{n,p,q}^{(0)} r_{n,p,q} = \sum_{i=1}^{I} \exp^{\{j2\pi(n\Delta f+f_0)(\tau_{p,q}^{(0)}-\tau_{p,q}^{(i)}\}}\sigma_i + \tilde{v}_{n,p,q} \quad (29)$$

$\tilde{v}_{n,p,q}$ is the noise after compensation. Then,

$$\tau_{p,q}^{(0)} - \tau_{p,q}^{(i)} = \frac{\|o-Z_p\|+\|W_q-o\|-\|h_i-Z_p\|-\|W_q-h_i\|}{c} \quad (30)$$

With,

Z_p the p-th transmitter et W_q the q-th receiver.

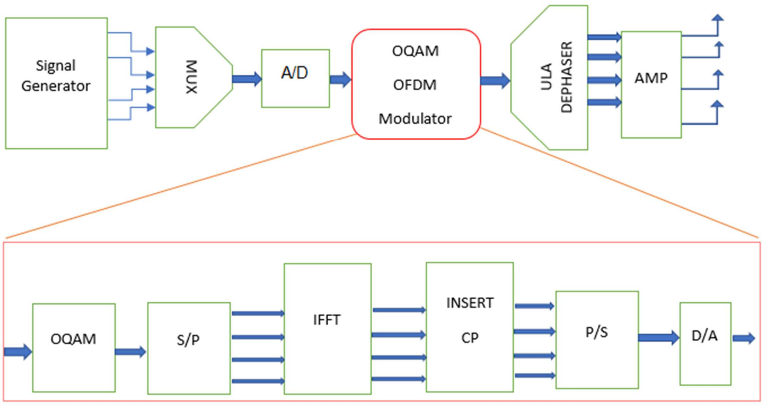

Figure 4. *MIMO Radar transmitter with OFDM OQAM.*

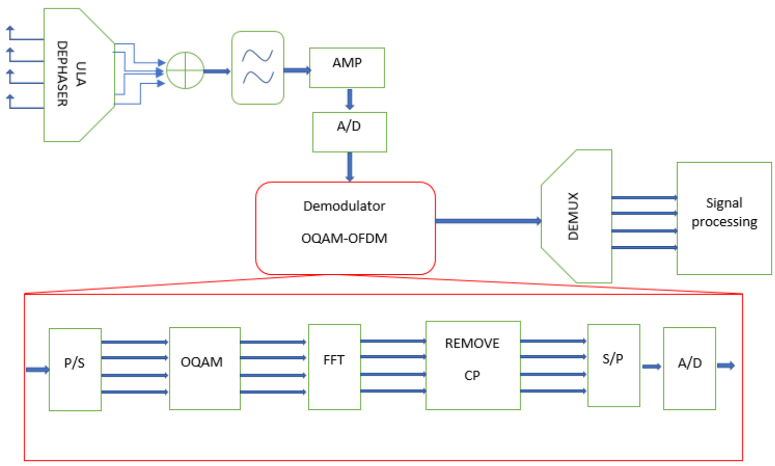

Figure 5. *MIMO Radar receiver with OFDM OQAM.*

The operators in the Figure 4 and Figure 5 are:

1) Signal generator: generate binary data to be sent.
2) MUX: Multiplexing the multiple signals generated to be sent on one channel.
3) A/D: Analog to digital.
4) S/P: Serial to Parallel.
5) IFFT: Inverse Fast Fourier Transform.
6) CP: Clipping.
7) ULA dehaser: Equation (10).
8) AMP: Amplifier.
9) D/A: Digital to Analog.
10) P/S: Parallel to Serial.
11) FFT: Fast Fourier Transform.

If $\tilde{\sigma}_i = \sigma_i \exp\{j2\pi\frac{(-2u_i+\mu_i)}{\lambda}\}$ designates the modulated dispersion amplitude phase, which is a constant for a transmitter/receiver chain.

$$\begin{cases}\Delta u = \frac{C}{2N\Delta f} \\ \Delta\tilde{x} = \frac{Cd_0}{Pf_0 d_t} \\ \Delta\tilde{y} = \frac{Cd_0}{Qf_0 d_r}\end{cases} \quad (31)$$

The radial distance could be expressed by the equation (31) and the section respectively, with $\lambda_0 = \frac{C}{f_0}$ being the wavelength of the system. Pd_t and Qd_r is the distances between the transmitters, and QD_r is the distance between the receivers.

$$u_i = \bar{h}_i^T d_0 \quad (32)$$

$$\bar{h}_i = h_i - o \quad (33)$$

$$(\tilde{x}_i, \tilde{y}_i, \tilde{z}_i)^T = \bar{h}_i - u_i d_0 \quad (34)$$

$$\mu_i = \left(\bar{h}_i - u_i d_0\right)^T (Z_0 + W_0) \quad (35)$$

With,

u_i: the radial distance;

The equation (36) expresses the signal received.

$$h_{n,p,q} = \varepsilon_{n,p,q}^{(0)} r_{n,p,q} = \sum_{i=1}^{I} \tilde{\sigma}_i . \exp^{\{j\pi\omega_{1,i} + jP\omega_{2,i} + jQ\omega_{3,i}\}} + \tilde{v}_{n,p,q} \quad (36)$$

$$\text{With,} \begin{cases}\omega_{1,i} = \frac{-2\pi\lambda_i}{N\Delta u} \\ \omega_{2,i} = \frac{2\pi\tilde{x}_i}{P\Delta\tilde{x}} \\ \omega_{3,i} = \frac{2\pi\tilde{y}_i}{Q\Delta\tilde{y}}\end{cases}$$

After the OFDM theory on transmitter and receiver signal, the OQAM processing could also be applied to it.

The equation (37) expresses the OQAM-OFDM modulated signal.

$$x(t) = \sum_{n=0}^{N-1} \frac{1}{\sqrt{N}} \exp^{\left(j2\pi\frac{tn}{N}\right)} s_n = V.S \quad (37)$$

N: Number of subcarriers of DFT;

V: Columns of IDFT;

S: Vector of symbol O-QAM.

s_n : Symbol OQAM carried by the n-th subcarrier expressed by the equation (38)

$$s_n(t) = \theta_{l,k}.a_{l,k}.\delta(t - k\frac{T_s}{2}) \quad (38)$$

2.4. MIMO Radar with UFMC-OQAM

The UFMC [11-13] divided into subband B with On UFMC filter having length L. The equation (39) expresses this modulated signal.

$$x(t) = \sum_{i=0}^{B} \sum_{l=0}^{L} \sum_{n=0}^{N-1} \frac{1}{\sqrt{N}} \exp^{\left(j2\pi\frac{nt}{N}\right)} s_{i,n}(t).f(l) \quad (39)$$

Where,

s_n : Symbol carried by the n-th subcarrier;

f: Characteristic filter function used on UFMC;

N: Number of subcarriers of DFT;

L: Length of the filter;

B: Number of sub-bands.

The equation (40) is derived by the equation (39) by simplifying this with summation.

$$\underset{[(N+L-1)\times 1]}{x(t)} = \sum_{i=0}^{B} \underset{[(N+L-1)\times N]}{F_i} \underset{[N\times n_i]}{V_i} \underset{[n_i\times 1]}{S_i} \quad (40)$$

S_i: Vector of symbol O-QAM for i-th subband;

V_i: Columns of IDFT corresponding to the i-th sub-band;

F_i: Filter with signal convolution and TOEPLITZ matrix.

The equation (41) expresses this matrix form.

$$x = \bar{F}.\bar{V}.\bar{S} \quad (41)$$

Where,

$$\bar{F} = [F_1\ F_2\ ...\ F_B]$$

$$\bar{V} = \mathrm{diag}\ [V_1\ V_2\ ...\ V_B]$$

$$\bar{F} = [S_1\ S_2\ ...\ S_B]^T$$

Unlike OFDM, on each IFFT, UFMC subdivides into K susb-band. Combined with OQAM, the OQAM UFMC will be represented by a fully diagram like on the Figure 6, and Figure 7.

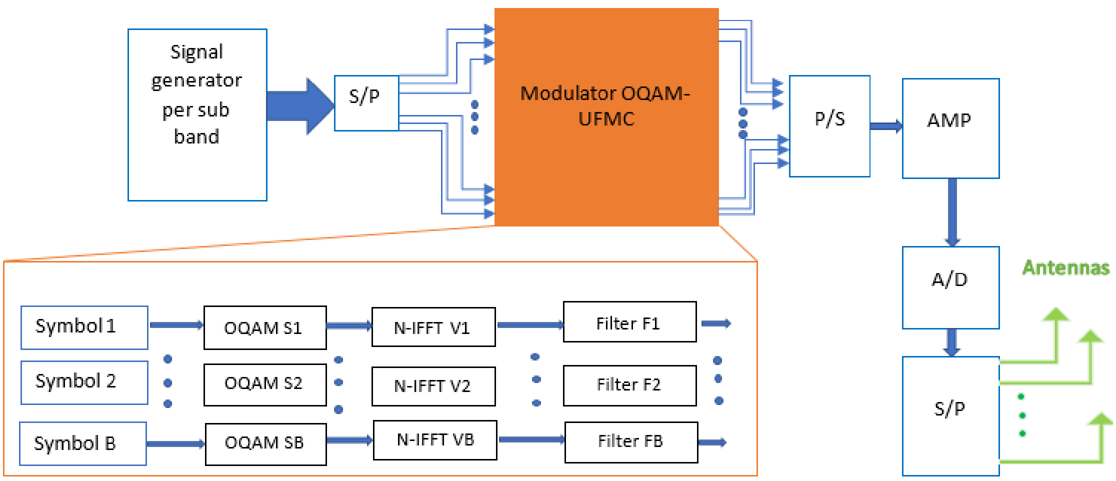

Figure 6. *MIMO Radar transmitter with UFMC OQAM.*

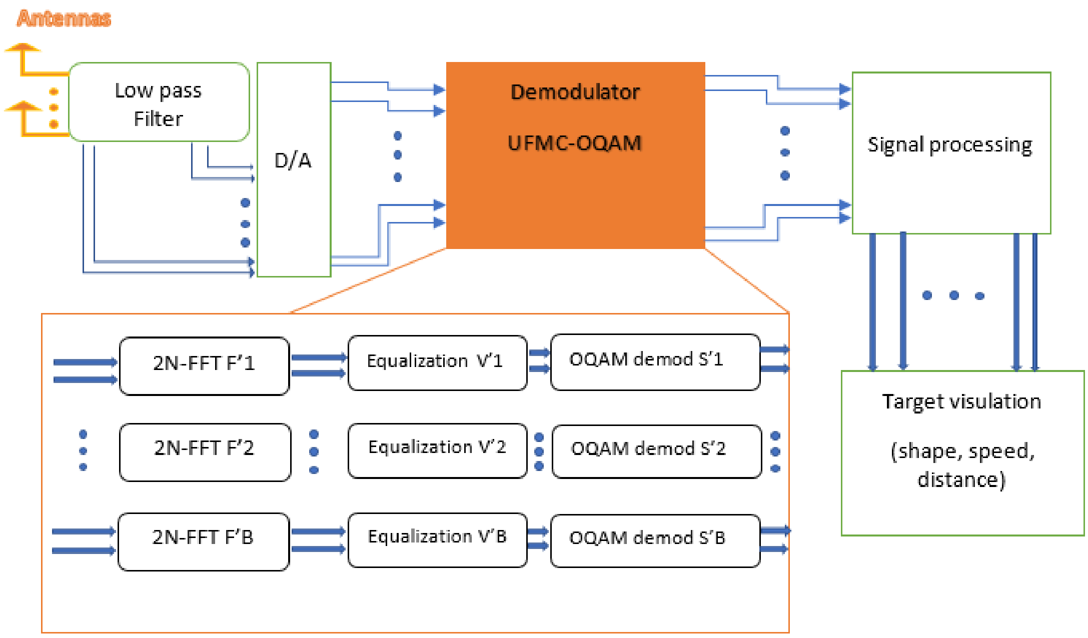

Figure 7. *MIMO Radar receiver with UFMC OQAM.*

2.5. MIMO Radar with FBMC-OQAM

A generalized filters permit a best time and frequency synchronization like on FBMC [14-16] diagram which is really inspired on OFDM. FBMC optimizes the resource uses with CP and has a good spectral containment.

With FBMC methods, the transmitter and receiver should use a filter bank which is doing with many filters represented like array.

A synthesis filter is the name of the filter bank at the transmitter analysis filter bank is for the receiver. For having multiple sub streams, the input uses serial to parallel and then the synthesis filter bank processes the parallel signal to be converted back to serial bitstream after going out of synthesis bank.

The synthesis filter will be compared to the analysis filter as on Figure 8.

A PolyPhase Network (PPN) is used to improve the filter on transmitter and on a receiver.

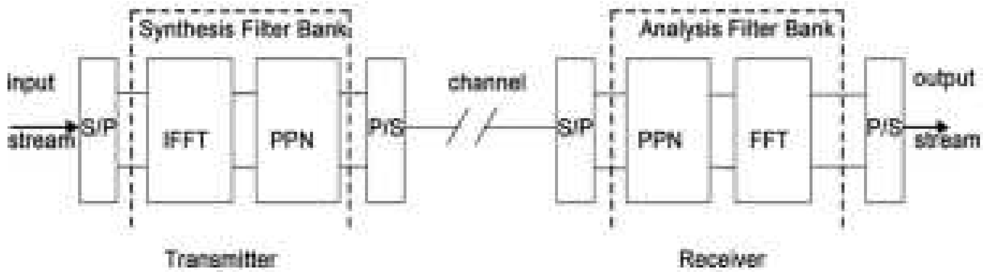

Figure 8. *Transmitter and receiver Filter.*

After the OQAM pre-processing, the OQAM symbols are shaped on the different sub-carriers by a bank of synthesis filters. In this condition, time and frequency will be at the correct localization of each sub-carriers using a special prototype filter. The equation (42) shows the output signal after the synthesis filter.

$$S(t) = \sum_{l=0}^{N-1} \sum_{k=-\infty}^{+\infty} j^{l+k} a_{l,k} h\left(t - k\frac{T_s}{2}\right) e^{j\frac{2\pi l}{T_s}t} \quad (42)$$

Where,
N: Number of subcarriers;
l: Index of frequency;
k: Index of time;
$a_{l,k}$: Symbol of OQAM;
$h(t)$: The impulse response of the prototype filter is used. The impulse response of a system is the output obtained when the input is an impulse, i.e. a sudden and brief variation of the signal.

So, for the beginning, our approach consists of using a prototype filter with impulse response. The input signal will be multiplied by the coefficients h_i. The equation (43) expressed the output signal noted by y:

$$y(k) = \sum_{i=1}^{L_p} h_i . x(k - i) \quad (43)$$

Where L is the length of the filter.

After the Fourier transform, the equation (44) expresses the filter obtained by the frequency response.

$$\mathrm{H(f)} = \sum_{i=1}^{L_p} h_i . e^{-j2\pi if} \quad (44)$$

Let $e^{j2\pi f} = Z$, The Z-transform will be expressed by the equation (45) and his result will be noted by H.

$$\mathrm{H(Z)} = \sum_{i=1}^{L_p} h_i . Z^{-i} \quad (45)$$

Where,

$$L_p = KN$$

K: Overlap factor;
N: Number of subcarriers.

By transforming by: $i = k'N + n'$ where $0 \leq k' \leq K-1$ and $0 \leq n' \leq N-1$ and by using the polyphase decomposition, the equation (46) permits to express the decomposed into N elementary of the filter.

$$\mathrm{H(Z)} = \sum_{n'=0}^{N-1} \sum_{k'=0}^{K-1} h_{k'N+n'} . Z^{-(k'N+n')} \quad (46)$$

$$\mathrm{H(Z)} = \sum_{n'=0}^{N-1} \left[\sum_{k'=0}^{K-1} h_{k'N+n'} . Z^{-(k'N)}\right] . Z^{-n'} \quad (47)$$

Let's pose $E_{n'}(Z^N)$ the n'-th expressed by the equation (48).

$$E_{n'}(Z^N) = \sum_{k'=0}^{K-1} h_{k'L+n'} . Z^{-(k'N)} \quad (48)$$

The equation (49) expresses the filter after the decomposition.

$$\mathrm{H(Z)} = \sum_{n'=0}^{N-1} E_{n'}(Z^N) . Z^{-n'} \quad (49)$$

When the prototype filter will be shifted N, the synthesis filter bank will be obtained. The equation (50) expresses each decomposition by using a frequency-centric i/N where I = 0, 1,…, N-1.

$$H_i(Z) = \sum_{n'=0}^{N-1} e^{j2\pi n'\frac{i}{N}} E_{n'}(Z^N) . Z^{-n'} \quad (50)$$

The equation (51) expresses the matrix representation of the synthesis filter bank by posing $w = e^{-j\frac{2\pi}{N}}$,

$$\begin{bmatrix} H_0(Z) \\ H_1(Z) \\ \vdots \\ H_{N-1}(Z) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & w^{-1} & & w^{-(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & w^{-(N-1)} & \cdots & w^{-(N-1)^2} \end{bmatrix} . \begin{bmatrix} E_0(Z^N) \\ E_1(Z^N) . Z^{-1} \\ \vdots \\ E_{N-1}(Z^N) . Z^{-(N-1)} \end{bmatrix} \quad (51)$$

Where, the square matrix is the inverse discrete Fourier transform matrix of order N.

The equation (51) expresses the implementation of the synthesis filter bank on the emitter by using the polyphase FBMC-OQAM.

In this, for the full representation of the synthesis filter and inspired by the equation (50), Figure 9 illustrates the polyphase decomposition which could reduce the implementation's complexity.

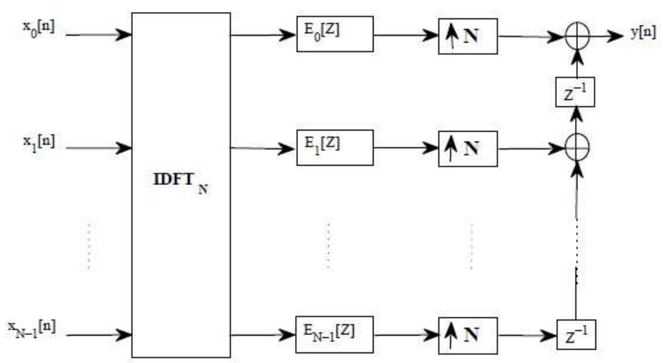

Figure 9. *FBMC using filter synthesis.*

Where, $\uparrow N$:the oversampling operation with the factor N.

Using same methods about the polyphase of the synthesis filter bank previously, the analysis filter bank could be expressed as the equation (50) for having the equation (52).

$$H_{-i}(Z) = \sum_{n'=0}^{N-1} e^{-j2\pi n'\frac{i}{N}} E_{n'}(Z^N) . Z^{-n'} \quad (52)$$

Similarly, the equation (53) expresses matrix representation of the analysis filter bank by posing $w = e^{-j\frac{2\pi}{N}}$.

$$\begin{bmatrix} H_0(Z) \\ H_1(Z) \\ \vdots \\ H_{N-1}(Z) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & w^{-1} & & w^{-(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & w^{-(N-1)} & \cdots & w^{-(N-1)^2} \end{bmatrix} . \begin{bmatrix} E_0(Z^N) \\ E_1(Z^N) . Z^{-1} \\ \vdots \\ E_{N-1}(Z^N) . Z^{-(N-1)} \end{bmatrix} \quad (53)$$

Where, the square matrix is the inverse discrete Fourier transform matrix of order N.

The equation (53) expresses the implementation of the analysis filter bank on the transmitter by using the polyphase FBMC-OQAM.

In this, for the full representation of the analysis filter and inspired by the equation (51), Figure 10 illustrates the polyphase decomposition which could reduce the implementation's complexity.

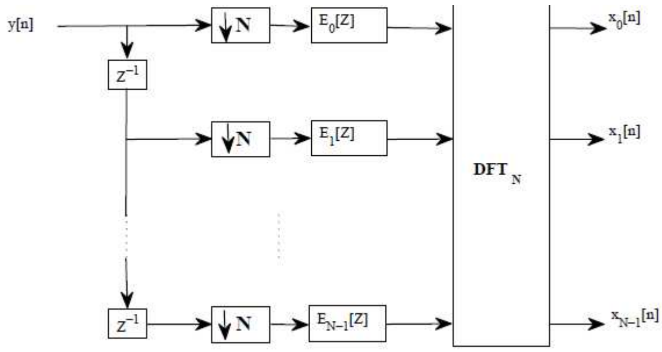

Figure 10. *FBMC with synthesis filter bank.*

For the prototype filter, many proposition could be experimented like: Gaussian function, rectangular window (for the case of OFDM), the IOTA filter (Isotropic Orthogonal Transform Algorithm), the PHYDYAS filter (Physical layer for dynamic spectrum access and cognitive Radio, etc.). The PHYDYAS filter is used for FBMC-OQAM.

Table 1. *The coefficients of the frequency response of the PHYDYAS filter for K=2, 3, 4.*

K	H_0	H_1	H_2	H_3
2	1	$\frac{\sqrt{2}}{2}$		
3	1	0.911438	0.411438	
4	1	0.971960	$\frac{\sqrt{2}}{2}$	0.235147

Bellanger proposed this PHYDIAS filter in 2001. So, the main principle is to determine the frequency coefficients and to build the frequency response from these coefficients and to generate the impulse response by using the inverse Fourier transform.

Determining which filter frequency coefficients are symmetric depends on the overlap factor $K = \frac{L_p}{N}$, where L_p is the number of coefficients of the impulse response of the searched filter and N is the carrier number. Table 1 shows the values of the coefficients of the frequency response of the PHYDYAS filter for K=2, 3, 4.

For K>4, the equation (54) expresses all case of coefficients.

$$\begin{cases} H_0 = 1, H_1 = 0.97195983, H_2 = \frac{\sqrt{2}}{2} \\ H_3 = \sqrt{1 - H_1^2}, H_k = 0 \text{ pour } 4 < k < L_p - 1 \end{cases} \quad (54)$$

The equation (55) expresses the frequency response of the filter.

$$H(f) = \sum_{k=-(K-1)}^{K-1} H_k \frac{\sin\left(\pi\left(f - \frac{k}{NK}\right)NK\right)}{NK\sin\left(\pi\left(f - \frac{k}{NK}\right)\right)} \quad (55)$$

The impulse response is obtained by using the inverse Fourier transform in the equation (55) for obtaining the equation (56).

$$h(t) = 1 + 2\sum_{k=0}^{K-1} H_k \cos\left(2\pi \frac{kt}{KT}\right) \quad (56)$$

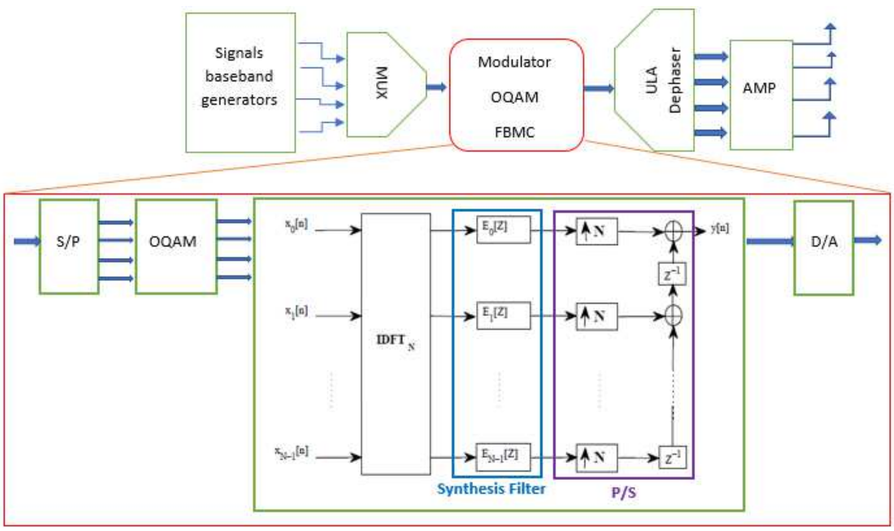

Figure 11. *MIMO Rada with FBMC OQAM transmitter.*

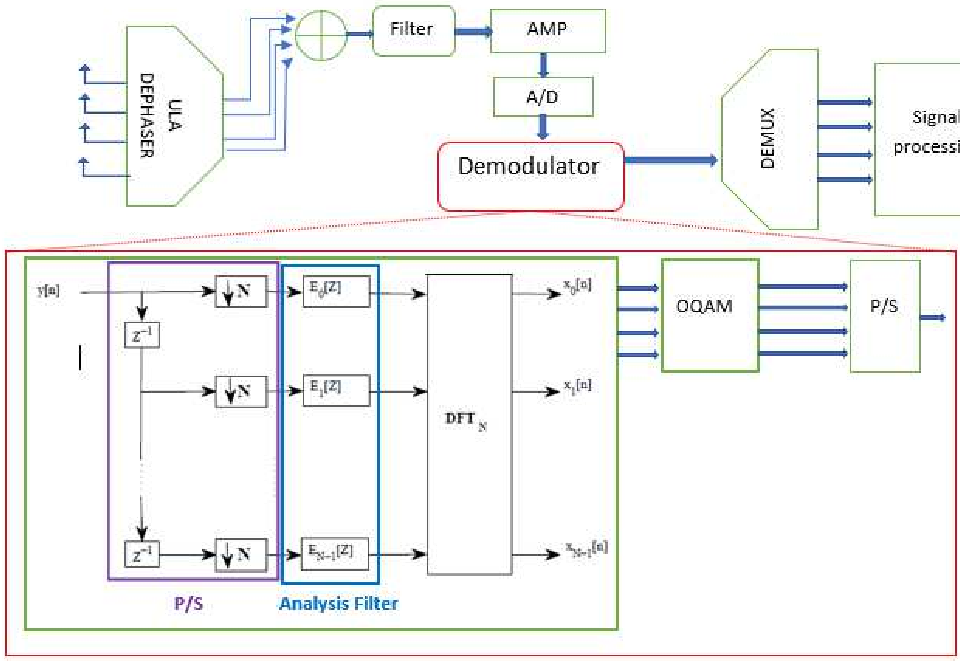

Figure 12. *MIMO Radar with FBMC OQAM receiver.*

3. Result and Interpretation

3.1. Plotting Generated Signal of Each Modulation

In this article, the three modulations: OFDM, UFMC, FBMC all have the generator signal. This generator uses a random signal binary by the rand function of Matlab. The multiplexer mixes the signal generated for sending to only one channel.

The three modulations use multi-carrier techniques. So, instead of only one frequency, multiple frequencies with orthogonal carries i.e. with the same space of frequency of each carry will send the signal.

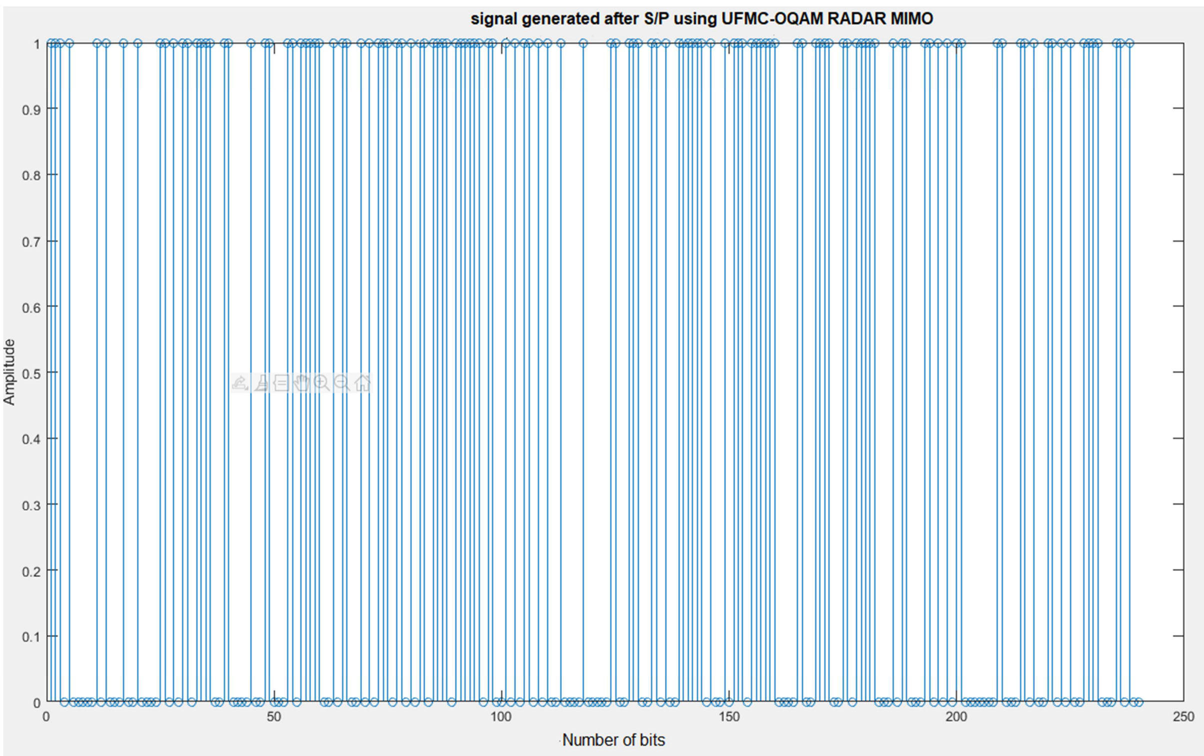

Figure 13. *Signal generated by RADAR MIMO after S/P using OFDM-OQAM.*

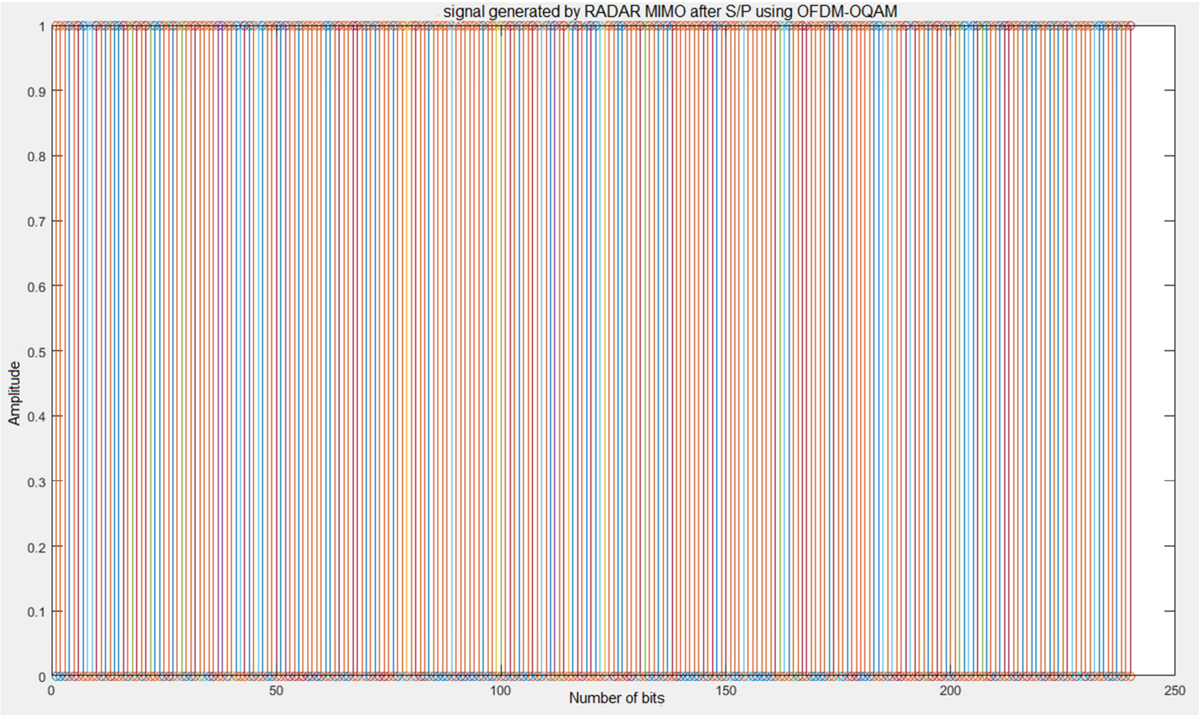

Figure 14. *Signal generated by RADAR MIMO after S/P using UFMC-OQAM.*

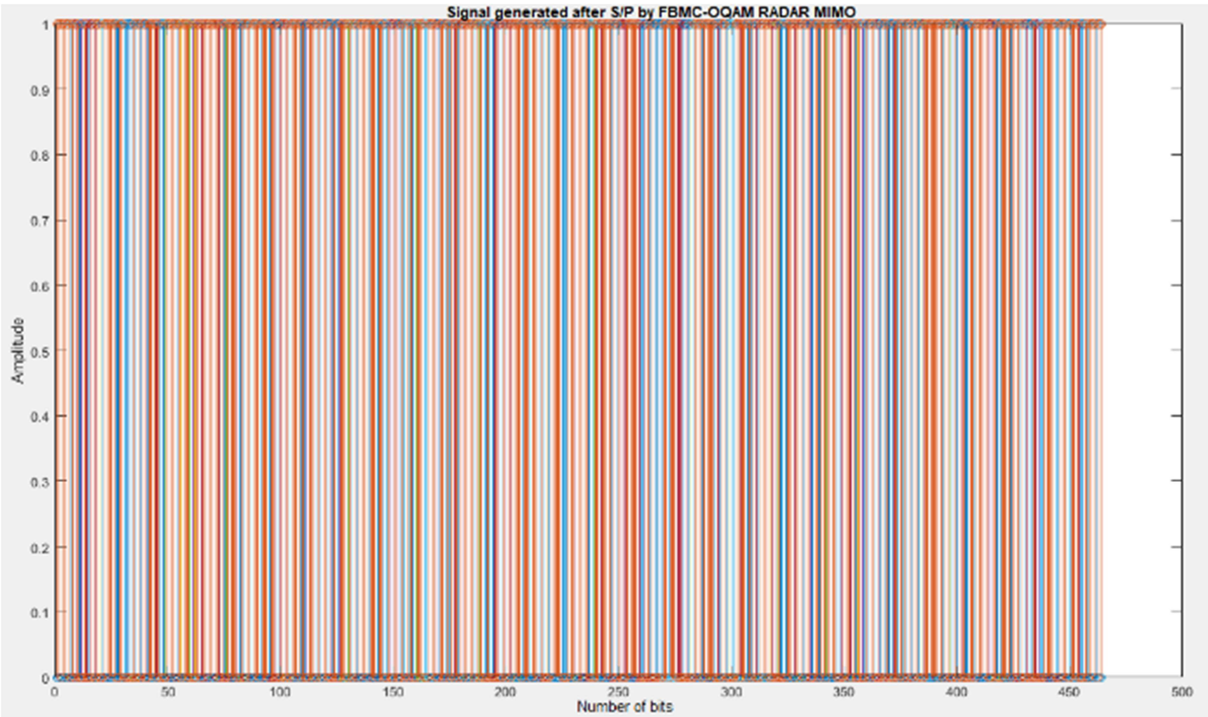

Figure 15. *Signal generated by RADAR MIMO after S/P using FBMC-OQAM.*

To achieve multi-carries, the Inverse of the Fast Fourier transform should be used to translate the time domain to be in the frequency domain. The input should be separate to have the same number of carries. So, the bloc of the serial to parallel transforms the signal to N-channel to be sent on each multi-carries using this IFFT.

In Figures 13, 14, 15, the signal generated will be plotted with colors of each number of subcarriers to be modulated resp. by OFDM, UFMC and FBMC.

3.2. Spectrum of Transmitter Bloc of Each Modulation

To be transported on a channel, the signal should be modulated. Generally, modulation is multiplying the signal between the signal generated by the oscillator and a bloc of filters will be used after this.

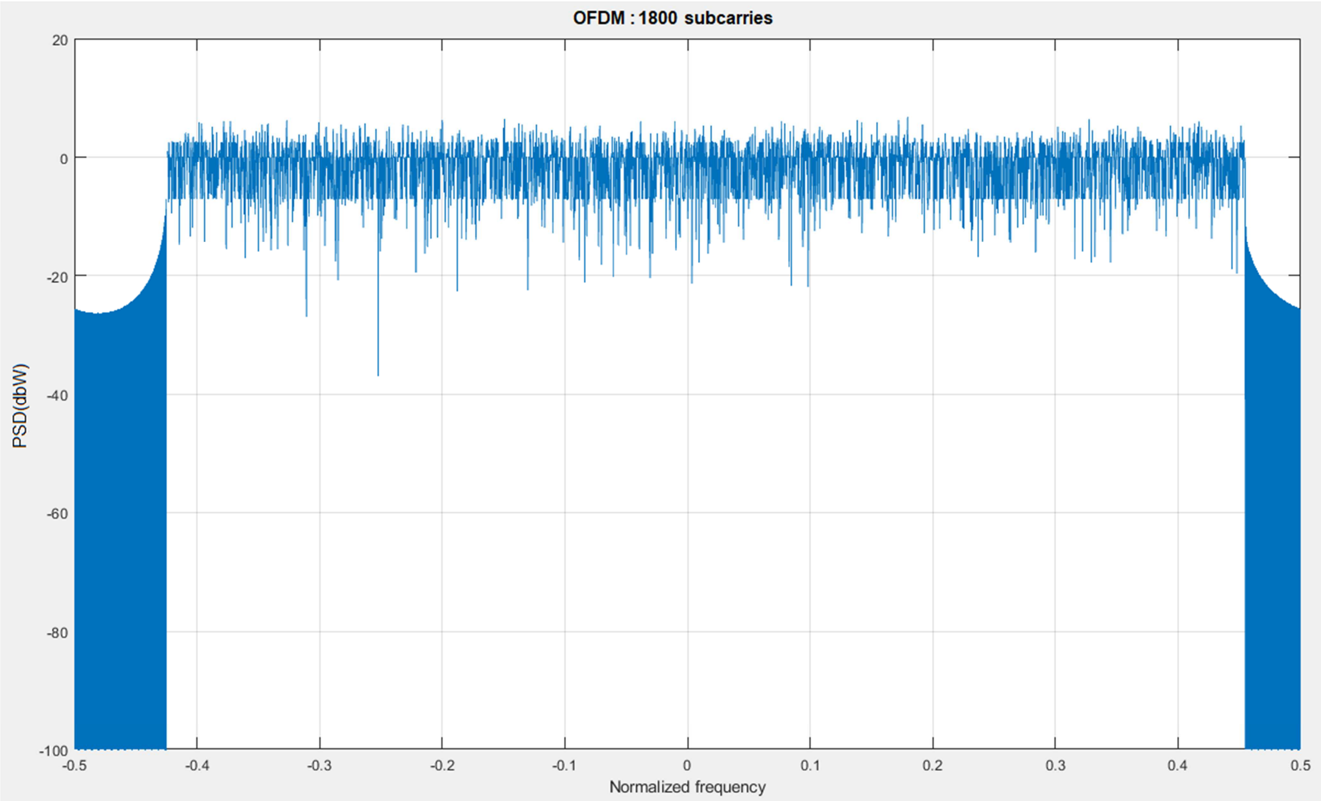

Figure 16. Spectrum analyzer using OFDM-OQAM.

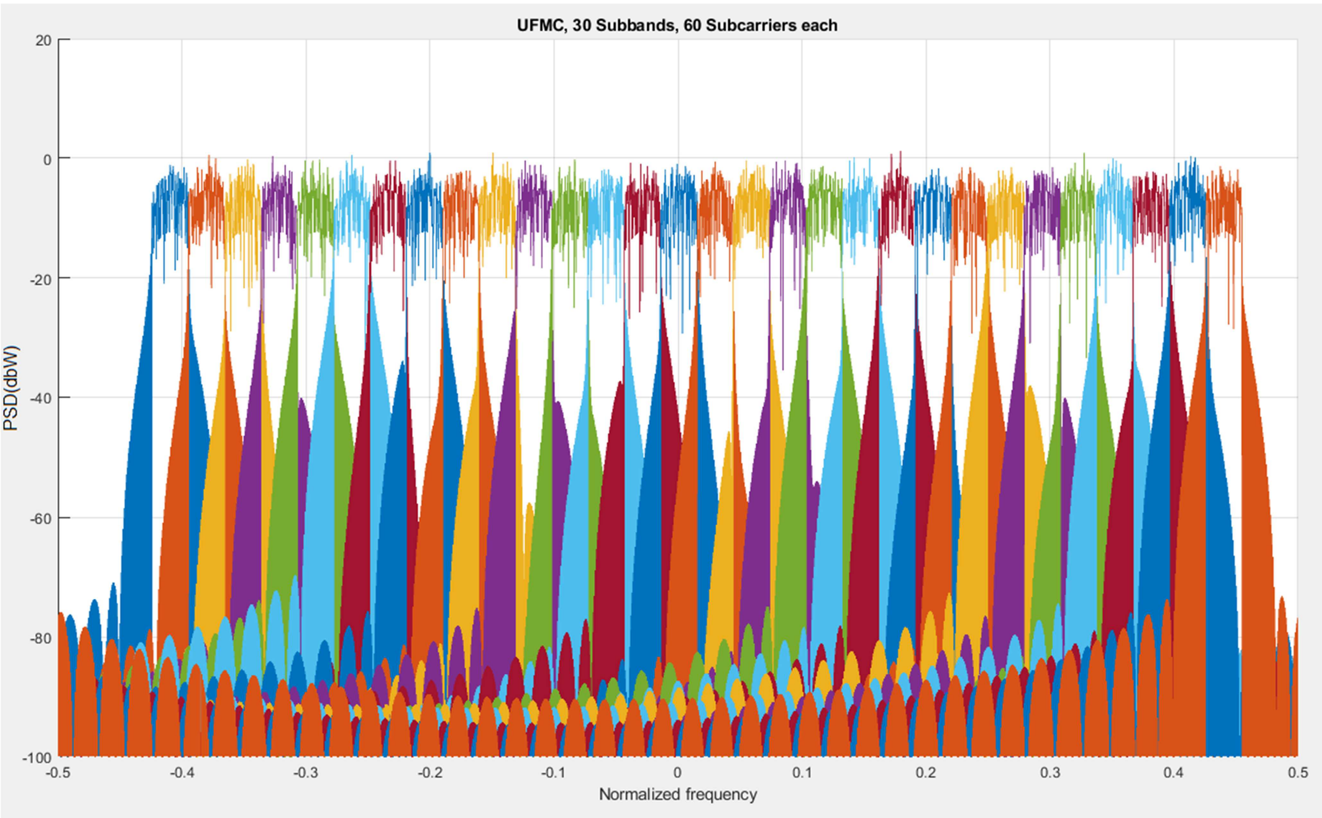

Figure 17. Spectrum analyzer using UFMC-OQAM.

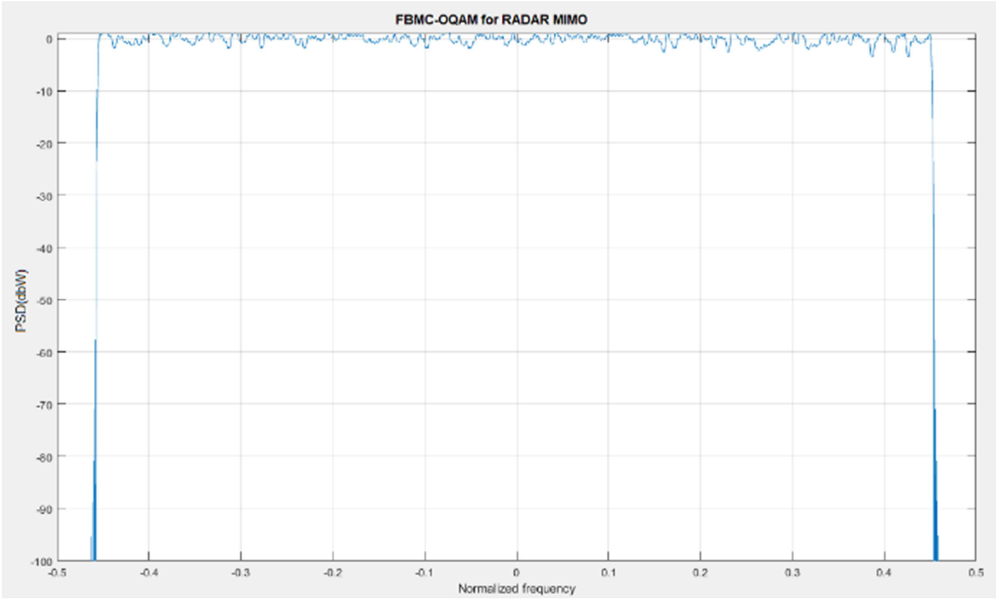

Figure 18. *Spectrum analyzer using FBMC-OQAM.*

The modulation OFDM uses multi-carrier modulations using IFFT with a rectangular filter. The modulation UFMC uses a sub band for each multi-carrier modulation with a rectangular filter per each sub-band. The modulation FBMC uses IFFT and filter for each sub-carry.

The schema bloc in Figures 4, 6, 8 will show how to implement resp. OFDM, UFMC and FBMC modulator. To see how the signal is in the frequency domain. The Power Spectrum Density (PSD) will be plotted by the spectrum analyzer resp. in the Figures 16, 17, 18.

The parameter chooses for this simulation for the OFDM is IFFT with 1800points of number.

Like UFMC uses multiple sub-bands, the subcarriers and sub-band should be configured. In our simulation, we used 60 points of IFFT and 30 sub-bands to be compared with the OFDM (1800points).

The demodulation is the inverse process of the modulation presented in Figures 5, 7, 9. After demodulation, without the transmission channel, the simulation shows the same result as on the signal generated.

To have more idea, we use Gaussian Channel modelization to show the effect of noise on the modulation.

3.3. Modulated Signal of Each Modulation

For each methods OFDM, UFMC, FBMC; the modulated signal will be represented in Figures 19, 20, 21.

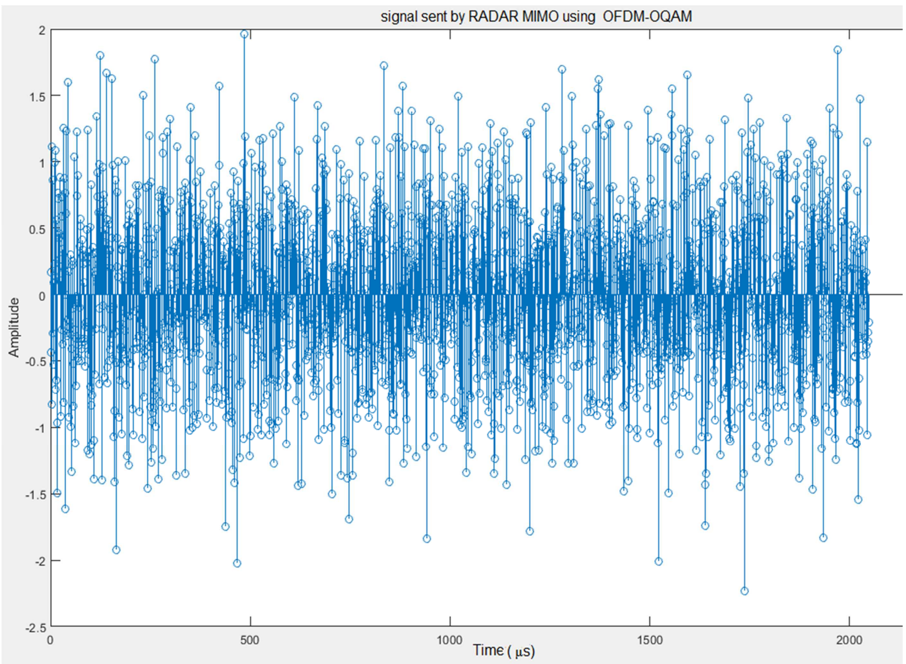

Figure 19. *Signal modulated using OFDM-OQAM.*

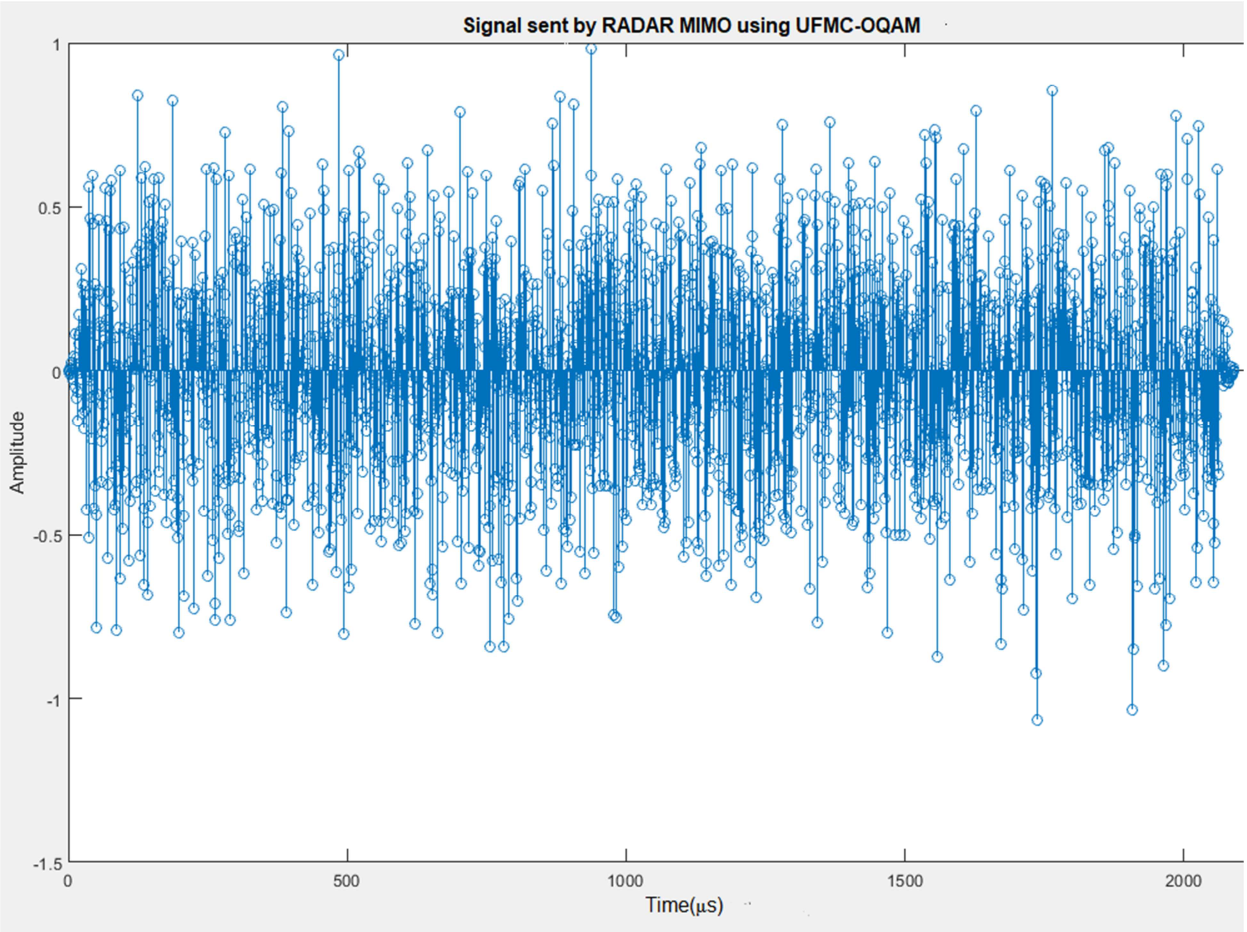

Figure 20. *Signal modulated using UFMC-OQAM.*

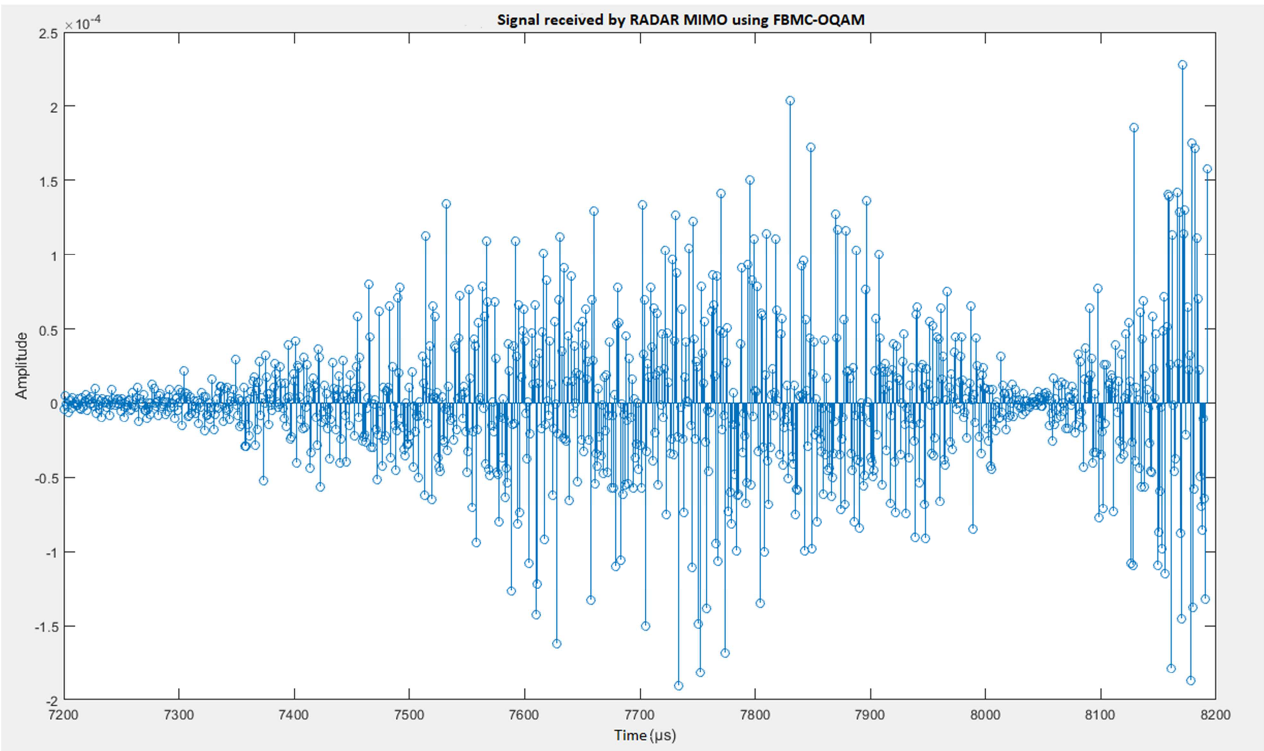

Figure 21. *Signal modulated using FBMC-OQAM.*

3.4. Analyze of out of Band

The ideal on the spectrum is to maximize the In Of band and minimized the Out Of Band (OOB).

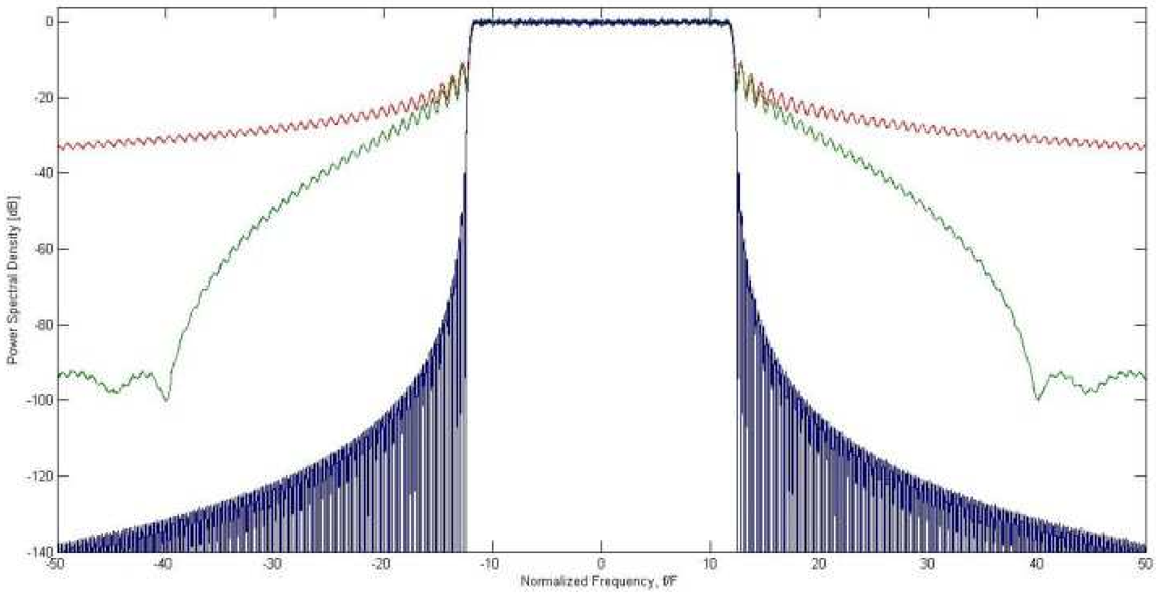

Figure 22. *Spectrum analyzer of the three methods OFDM-OQAM, UFMC-OQAM and FBMC-OQAM.*

For each modulation OFDM, UFMC and FBMC we can see the spectrum of the signal. On the In Of Band, the surface all occupied approximatively the same. To have a more precise idea, the Out Of Band of the FBMC in blue color has the minimum OOB. The UFMC with the right color is the second for having the minimum OOB and the OFDM with red is the last for having the minimum OOB. The OOB will be presented on the Figures 23, 24.

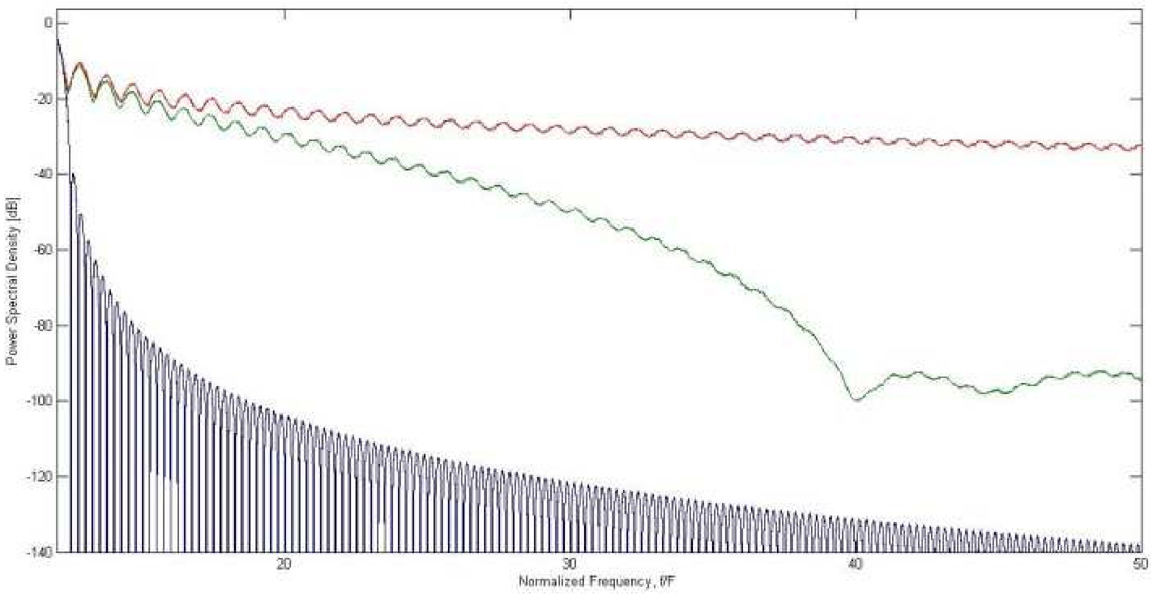

Figure 23. *Out of band of right part of the three methods OFDM-OQAM, UFMC-OQAM and FBMC-OQAM.*

Studying OOB is very important because, having a large surface of OOB could spent a lots of power consumption which could be appeared as thermal loss dissipated on the amplification. The device is not economical in terms of energy if the out of band of spectrum is big. The second effect is also the harmonic could disturb other frequencies near this.

The O-QAM is selected in this article due to the robustness of the doppler, which appears frequently on the MIMO RADAR because the signal will be sent separately between the real part and the imaginary part.

Consequently, in terms of energy consumption and reducing harmonic frequency, the FBMC is the best option. The combination of FBMC-OQAM also gives a good result indeed to the doppler effect.

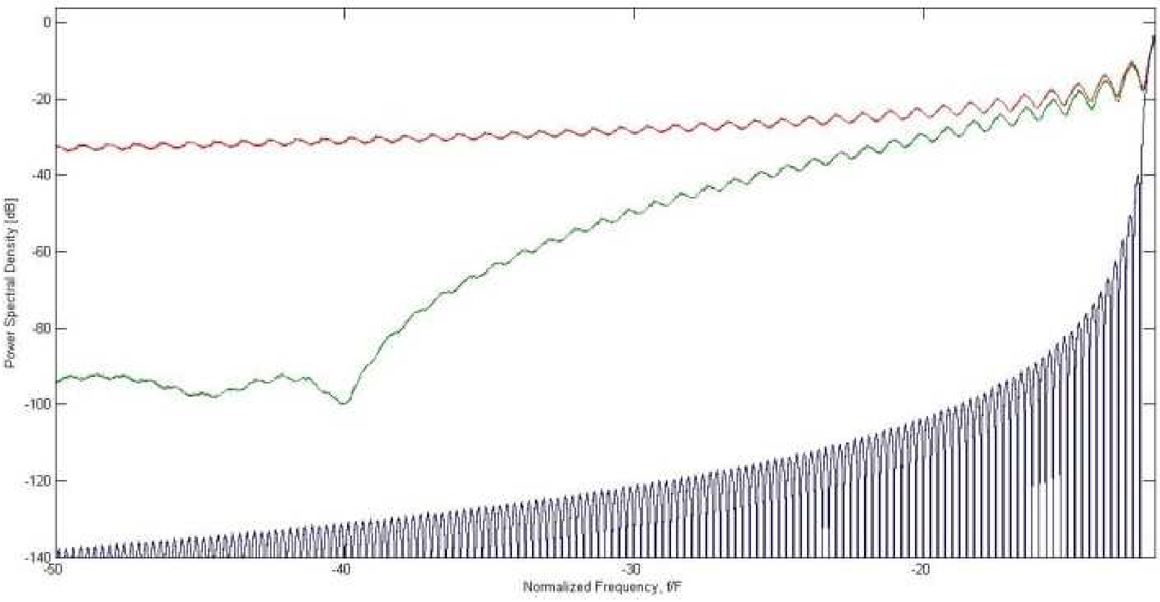

Figure 24. *Out of band of left part of the three methods OFDM-OQAM, UFMC-OQAM and FBMC-OQAM.*

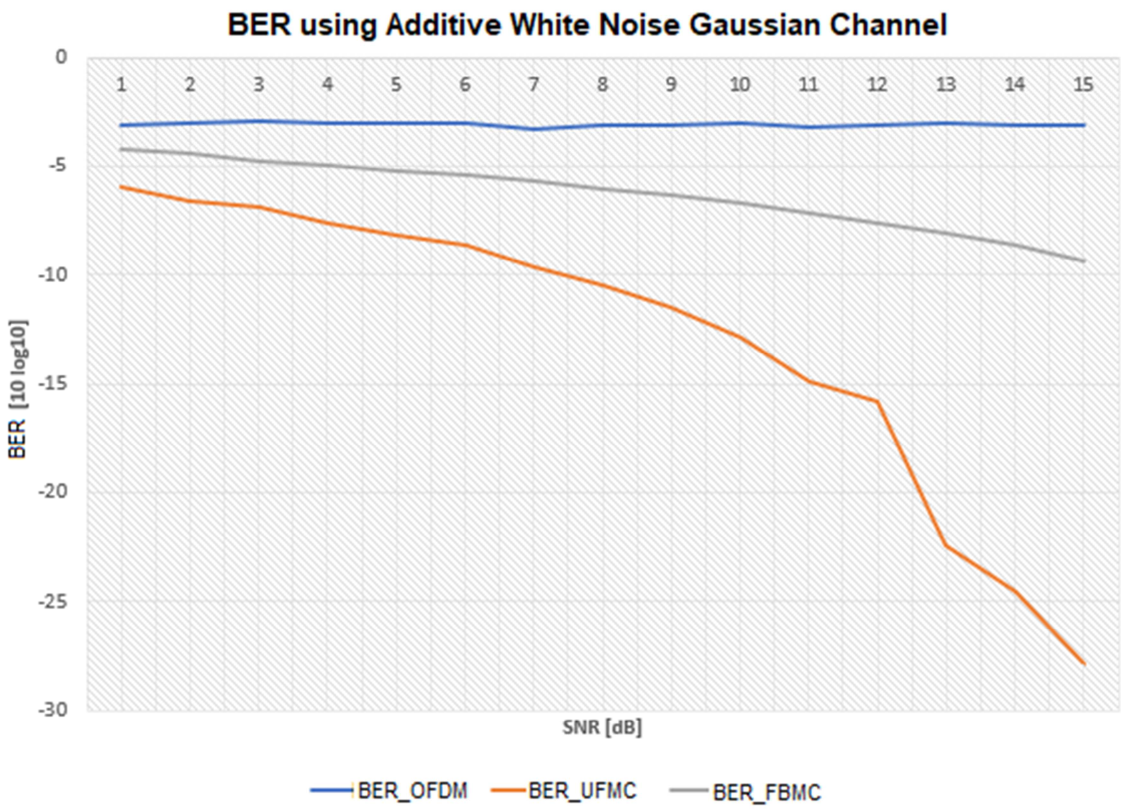

Figure 25. *BER of the three methods OFDM-OQAM, UFMC-OQAM and FBMC-OQAM.*

3.5. Analyze of BER

The BER is a percent of error bit with the bit transmitted. When the BER is minimal, the quality of data transmitted is the best. So, after seeing the results in Figure 25, UFMC presents a good data rate; after that, it's the FBMC and the last is the OFDM.

3.6. Analysis of Correlation and MSE

Table 2. *Table comparing the signal send and receive when SNR = 15db.*

	UFMC	OFDM	FBMC
MSE	14,46	28,62	14,31
CORRELATION	98,5	87,15	98,46

To verify the similarity of the signal sent and signal received, the two indicators: MSE (Minimum Square Error) and Correlation. They will be calculated and Table 2 shows that the UFMC presents the most similarity of signal sent and received, which is 98.5%.

4. Conclusion

This article shows how to implement O-QAM with advanced modulation used on 5G indeed OFDM, UFMC and FBMC. The OFDM uses IFFT for having multiple carries. The UFMC is like the OFDM but uses multiple sub-bands and the FBMC uses multiple filters per sub-carries. We propose comparing these 3 (three) methods with RADAR MIMO. So the decision is not really about high data rates, but about power consumption and about the doppler effect. The reason for using O-QAM is to reduce this effect. In conclusion, FBMC is the best way to reduce power consumption compared to the three modulations due to this out of band on spectrum very minimal. When we modelized the receiver, after calculating the similarity, this modulation also offers a good similarity of signal with a value near 98%.

As a perspective, we conclude that using multi-carrier modulation provides a high Peak Average Power Ratio (PAPR). The reduction of PAPR or adding predistortion could improve the advanced modulation combined with MIMO radar.

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