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Maximization of the power of the ultra-wide band "UWB" signal sent to the human body while respecting the Federal Communications Commission "FCC" constraints

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Abstract— The aim of this work is to maximize the power of the Ultra -Wide Band Signal "UWB" sent to the human body while respecting the constraints of the Federal Communications Commission "FCC". The signal is formed by Gaussian monocycle pulses and characterized by its center frequency "fc", the recurrence period of the pulses "PRI" and their amplitude "A".

To maximize the signal strength with FCC constraints, we have to try to approach the DSP cycles of these ultra-wide band frequency domain single-Gaussians with respect of the FCC constraints. For this, we used two approaches to validate the obtained results. The first one is the random variable theory which study phenomena characterized by randomness and uncertainty. It forms with the statistical science, an integral part of mathematics. In the second part, we used the approach by the genetic algorithm. Genetic algorithms (GA) are adaptive methods for solving optimization problems. They help find a solution to a problem involving a set of recurring random elements in a space encompassing a number of possible solutions. We also imposed 0,025 as a maximum duty cycle between the center frequency and PRI to avoid overlap between pulses.

This signal is used to be sent to the human body to detect heart beats. To see the waveform near the heart, we first modeled the human body as consisting of four semi-infinite layers. These layers are characterized by their complexity relative dielectric constant, thickness and electrical conductivity. Second, we use the Finite Difference Time Domain (FDTD) to model the UWB propagation channel. This method is a good tool to predict the distribution of electromagnetic field along the propagation channel.
In comparing the two approaches, we try to converge to an optimum solution validated by both approaches, characterized by maximum energy sent to the target and results in a signal capable of capturing information about heartbeat.

Index Terms— Ultra-wide band "UWB", Federal Communications Commission "FCC", Finite Difference Time Domain (FDTD), Genetic algorithms (GA), random variable theory, Gaussian monocycle, propagation channel

1 INTRODUCTION

Optimization plays an important role in operational research (a domain on the frontier between computing, mathematics and economics), applied mathematics (fundamental for industry and engineering), analysis and numerical analysis , in statistics for the estimation of the maximum likelihood of a distribution, for the search for strategies within the framework of game theory, or in theory of control and command. Many systems that can be described by a mathematical model are optimized. The quality of the results and predictions depends on the relevance of the model, the efficiency of the algorithm and the means for digital processing.
In this context, this work proposes to maximize the power of a UWB signal formed by a Gaussian monocycle pulse while remaining under the constraints of the FCC. This amounts to determining the characteristics of this signal: the central frequency of the pulse, the repetition frequency and the amplitude.
Ultra-Wide Band (UWB) technology is an emerging field in research. In fact, it can provide high throughput for wireless telecommunications applications. Because of its low power spectral density, UWB can be used in applications requiring a low probability of detection. It is also used by the radar for the beamforming [1]. The feasibility of UWB radar devices will be approved in the medical field. In fact, the new generations of UWB radar systems on chips do not change from one day to another [2]. But all systems are limited by a power barrier imposed by the Federal Communications Commission (FCC). Indeed, there is an authorized maximum power density (PSD) for UWB devices and it has been put to very low values (-41.3 dBm / MHz between 3 to 10 GHz) [3].
However, when the FCC imposed the limits of the effective isotropic radiation power (EIRP) for ultra-wide band systems (UWB), a problem to fitting the spectrum for UWB systems had appeared [4]. Indeed these systems existed before this mask. In addition, in Europe and Asia, other power spectral density levels was defined differently. That is why at the beginning, the UWB pulse modulated systems, had to be efficient in the spec+tral point of view, that is to say, it must have as energy as possible while being in accordance with a given spectrum mask.[5].
The FCC sets the power levels need by the FCC in the US for

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indoor UWB devices [6].

TABLE 1
LIMITS OF POWER ESTABLISHED BY THE FCC.

FREQUENCY [MHZ]	EIRP [DBM]
0-960	-41.3
960-1610	-75.3
1610-1990	-53.3
1990-3100	-51.3
3100-10600	-41.3
> 10600	-51.3

FCC imposed very low power spectral density limit which does not exceed -41.3 dBm / MHz power (EIRP). And only the frequency band between 3.1 and 10.6 GHz had be allocated for radar systems.

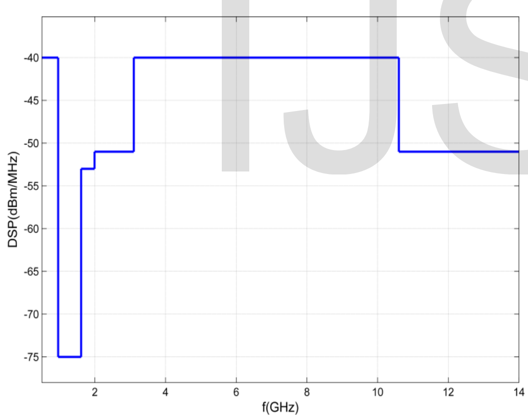

Fig. 1. FCC spectral mask for indoor systems

The power spectral density of an UWB impulse [7] sent by an antenna impedance R is defined as follows:

$$\mathrm{PSD}(\omega) = \frac{\left(\tilde{\mathrm{f}}(\omega)\right)^2}{\mathrm{R.T_s}} \qquad (1)$$

With:

A: Antenna Resistance
TS: the pulse period expressed in (ms); Ts is the reciprocal of PRI.
$\tilde{f}(\omega)$: Fourier transform of the function f (t)
ω: the angular frequency in rad /s

To overcome its difficulties, there are many approaches that respect the limits of energy imposed by the FCC, some approaches use derived from Gaussian pulse, indeed their spectra become increasingly adapted to the constraints of the FCC if we increase the order of the derivative. The derivative of order five seems to be the best solution under the constraints of the FCC like we can see on the following [8].

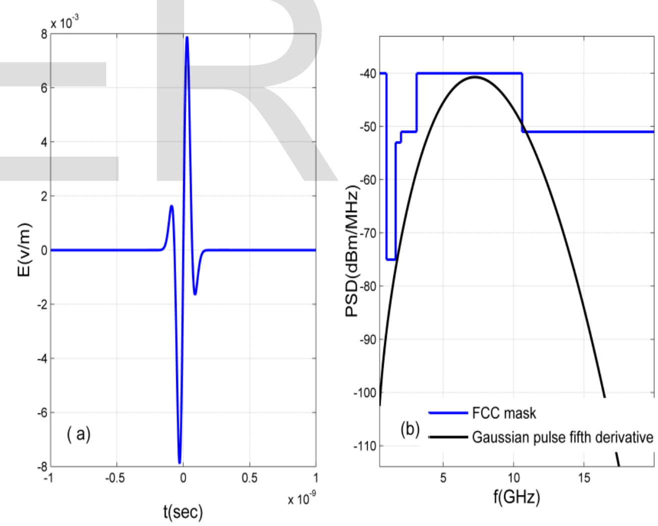

Fig. 2. Fifth derivative of the Gaussian pulse [8]

One of the others techniques is improving the capacity of the UWB pulse system. This approach uses multiple pulse waveforms which are mutually orthogonal. This can be done either in an M-ary signaling system where M is an element of a set of signaling orthogonal UWB pulses. Or by using a signaling diagram in which each pulse of the set is used as a bearer for a certain modulation of pulse amplitude modulation (PAM), wherein a change of binary phase (BPSK). In these cases the pulses are radiated simultaneously. [5], [9]
There are also some systems that adopt kinds of adaptive modulation based on the modulation 64/16/4 QAM (Quadra-

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ture Amplitude Modulation). Experimentally studies have shown that the system can obtain: high bandwidth, high data, high data capacity and immunity to electromagnetic interference.[10]
But all these systems, which are limited by the constraints imposed by the FCC, are characterized by the complexity of their design, despite the simplicity of the limits imposed by the FCC in the Ultra Wide Band "UWB" field, where the maximum power spectral density mask (PSD) authorized for UWB devices was set to very low values (-41.3 dBm / MHz in the 3.1 to 10.6 GHz frequency range). [3]
This manuscript consists of 5 sections: In section 3, we are interested in studying the system to optimize. Section 4 deals with signal energy maimization by the genetic method and the random variable method. In the last part, we presage the results of the two methods

2 Studied System

Our researches are to resolve a power balance for a radar based on a UWB transceiver dedicated to communications. We try also to follow a radar signal during its propagation in the different layers of human tissue.

2.1 Description of the propagation medium

The medium in which the UWB Ultra-Wide Band wave propagates, is modeled as the assembly of four layers (Figure 3 and table 2) [4], [6] laminated one after the other and each characterized by its thickness.

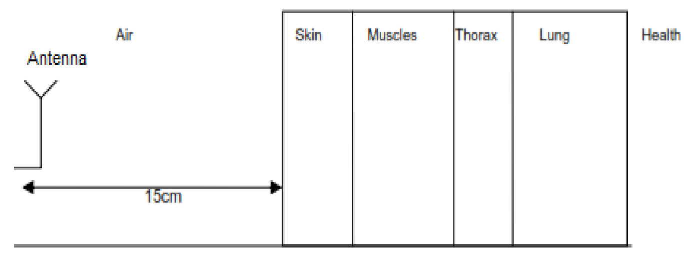

Fig3. Simplified model of human tissues composed of 4 semi-infinite

TABLE 2
THICKNESS OF THE VARIOUS LAYERS OF HUMAN TISSUE.

Type of layer	Thickness [cm]
Fat	0.96
Muscle	1.35
Cartilage	1.16
Lung	0.578

The source "antenna" is located at a distance of 15 cm from the air /fat interface.

2.2 Description of the FDTD method which describes the propagation of waves ULB

The FDTD is a numerical method for modeling the propagation of waves in space using a spatial and temporal discretization. In particular in the field of electromagnetic waves, where we use a interleaved one dimensional FDTD grid. [11],[12]
The interest of using this method is to see the shape of the signal at the heart place to see if the signal whose performance is found closest to the constraints of the FCC. The electric field is directed along the x-axis and the magnetic induction along the y-axis, the one-dimensional FDTD Maxwell's equations are written as follows:[11]

$$\tilde{E}_x^{n+\frac{1}{2}}(k)=\frac{\left(1-\frac{\Delta t.\sigma}{2\varepsilon_0\varepsilon_r}\right)}{\left(1+\frac{\Delta t.\sigma}{2\varepsilon_0\varepsilon_r}\right)}\tilde{E}_x^{n-\frac{1}{2}}(k)-\frac{\frac{1}{2}}{\left(1+\frac{\Delta t.\sigma}{2\varepsilon_0\varepsilon_r}\right)}\left(H_y^n\left(k+\frac{1}{2}\right)-H_y^n\left(k-\frac{1}{2}\right)\right)$$

$$H_y^{n+1}\left(k+\frac{1}{2}\right)=H_y^n\left(k+\frac{1}{2}\right)-\frac{\Delta t}{\Delta z\sqrt{\mu_0\varepsilon_0}}\left(\tilde{E}_x^{n+\frac{1}{2}}(k+1)-\tilde{E}_x^{n+\frac{1}{2}}(k)\right) \qquad (2)$$

Where k is the distance counter such that the total simulated distance is z = k·Δz, and n is the time counter such that the total simulated time is t=n·Δt; with Δz and Δt stand for the cell size and the time step respectively. This code was developed in [13] and [14] where we will have corrected at interfaces by the addition of an additive mesh.

2.3 Source impulse model

In the following, we adopt these two criteria to find the characteristics of the Gaussian unicycle pulse (amplitude, pulse width and repetition frequency) suitable for our application because this type of pulses is very simple to produce.

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Generally, UWB communication devices use the derived of the Gaussian pulse. For these reasons, this work follows the approach taken by Time Domain Corporation [11]. This approach known as PulsON® technology emit ultra-short "Gaussian monocycles" [12] which correspond to the first derivative Gaussian pulse. In the literature, they are defined as Gaussian monocycles. Moreover those pulses have the following form:

$$V(t) = \frac{2At}{\tau^2} \exp\left(-\left(\frac{t}{\tau}\right)^2\right) \qquad (3)$$

Where "τ" is a function of the center frequency "fc"

$$\tau = \frac{1}{\pi\sqrt{2}\, f_c} \qquad (4)$$

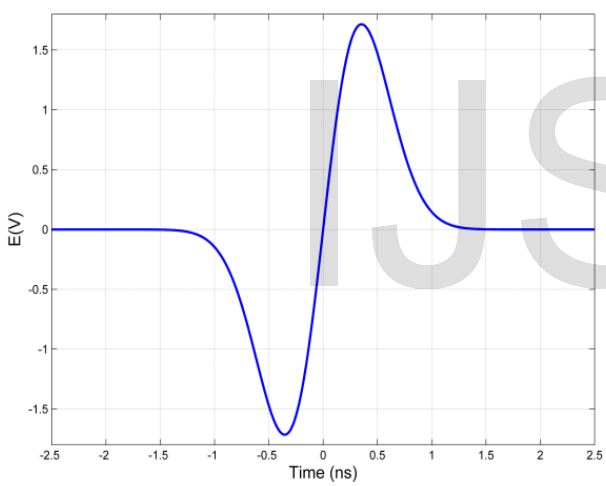

Fig4. Gaussian monocycle

The spectrum of the Gaussian monocycle pulse is given by the Fourier transform (equation 5):

$$\tilde{f}(\omega) = \frac{i.A.\omega.\tau}{\sqrt{2}} \exp\left(-\frac{\omega^2\tau^2}{4}\right) \qquad (5)$$

Where ω is the angular frequency.
The shape of this pulse in the frequency domain is given by Figure 5.

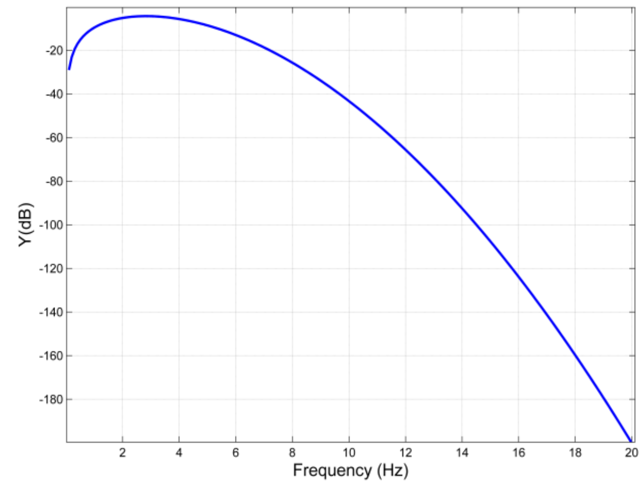

Fig5. Spectrum of the pulse Gaussian monocycle.

In the following, we will explain the criteria to look for the characteristics of the Gaussian monocycle pulse (amplitude, pulse width and repetition frequency) suitable to send to the target with maximum energy remaining under constraints FCC.

3 Maximizing the Power of a UWB Signal

We want to maximize the power of a UWB signal formed by monocycle Gaussian pulse while remaining under the constraints of the FCC. This amounts to determining the characteristics of this signal which are; the central frequency of the pulse, the repetition frequency and amplitude. So, we will compare the power spectral density (PSD) of a Gaussian pulse mask with the EIRP imposed by the FCC.

To maximize the power delivered to the target, we try to approach the DSP signal as close as possible to mask the FCC. (Figure 6)

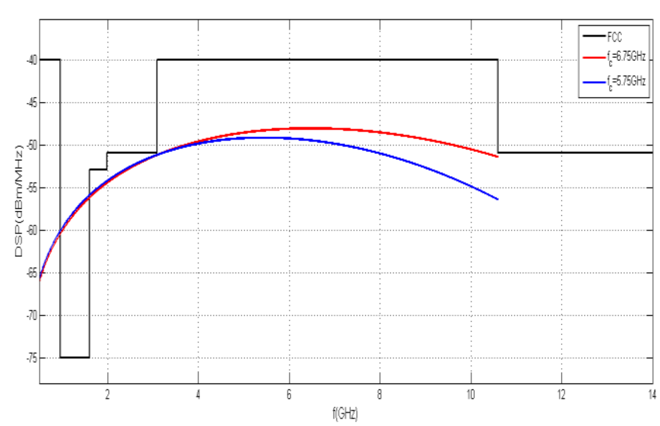

Fig 6. PSD monocycle Gaussian pulses with fc equal to 5.75 and 6.75 GHz

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We chose two techniques to maximize power :
The random variable
The genetic algorithm
3.1 Description of Random variable method
As close as possible to the PSD mask of the FCC, we take into consideration the following conditions:
• At the center frequency, we must have the maximum energy

$$PSD\left(\omega = 2x\pi x f_C\right) \le -413\ dB \qquad (6)$$

• At the frequency 10.6 GHz, PSD satisfies the following relationship:

$$PSD\left(\omega = 6.6602\times10^{10}\right) \le -51.25\ dBm \qquad (7)$$

• At the frequency 3.1 GHz, the PSD satisfies the following relationship:

$$PSD\left(\omega = 6.6602\times10^{10}\right) \le -51.25 dBm \qquad (8)$$

Due to these constraints, we randomly seek more signals which satisfy the constraints given above as shown in Figure 7.

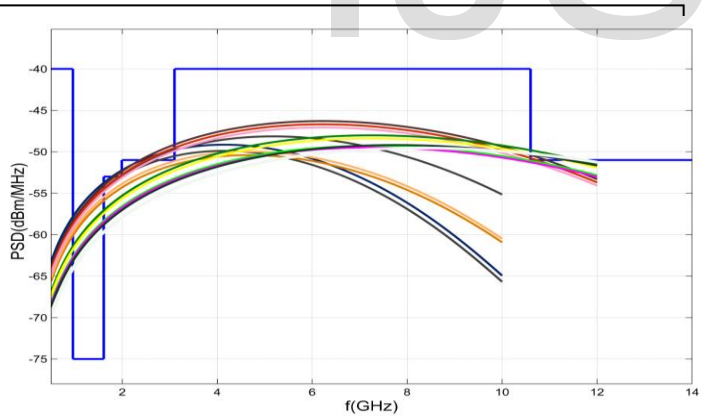

Fig 7. PSD of Gaussian monocycle pulses for different fc values, PRI and amplitude A

Approximately, the optimal solution is obtained for the center frequencies around 6 to 7.5 GHz where PSD at these frequencies show evidence of intersections with the mask of the FCC at the boundaries of the UWB band (3.6 GHz to -51 dBm and 10.6 GHz to -51 dBm) which gives a maximum power of -45 dBm around (very close to -41.3 dBm: the FCC barrier in the UWB band) located in the center of the band.
The random variables theory can be a solution to find an optimum solution. The characteristics of random variables satisfy the following system of equations [15], [16]:

$$\begin{cases} Y = \mathrm{Max}(f_c, PRI, A) \\ Y_i = \int_{-\infty}^{x} \left(\frac{1}{\sqrt{2\pi\sigma}} e^{\frac{(x-\eta)^2}{2\sigma^2}} dx \right) \end{cases} \qquad (9)$$

With:

η: The average of random variables .
σ: The standard deviation of random variables

The average is given by the following relationship:

$$\eta = \frac{1}{N}\sum x_i \qquad (10)$$

The standard deviation is determined from the following relationship:

$$\sigma = \sqrt{\mathrm{Variance}}$$
$$\mathrm{Variance} = \frac{1}{N}\sum (x_i - \eta)^2 \qquad (11)$$

The optimum value is calculated by the following relationship

$$Y_i = \sum \left(\frac{1}{\sqrt{2\pi\sigma}} e^{\frac{(x_i-\eta)^2}{2\sigma^2}} \right) \qquad (12)$$

.2 Description of Genetic algorithm
he genetic algorithm (GAs) [17] is inspired by biological evoution. It's effective field of independent research methods. ndeed, these methods allow us to solve problems in different pplication domain. The GAs are supported on the population hat are potential solutions in the research. To fix a potential olution, GAs control its evolution by payoff, gain, reward or bjective. This function assigns a scalar gain to a particular olution.
irst, GAs creates a random number, called the size of the chains of the population to form the first generation. Next, the payoff function evaluates each solution in this first generation. Higher payoffs yield the best solutions. Then based on these evaluations, genetic operations generate the next generation. The evaluation and generation are performed iteratively until the optimal solutions are discerned or the time allowed for calculation purposes [17], [18], [19].
Figure 8 shows the GA stream evolution. The equation (6) and (7) are introduced into the selection function

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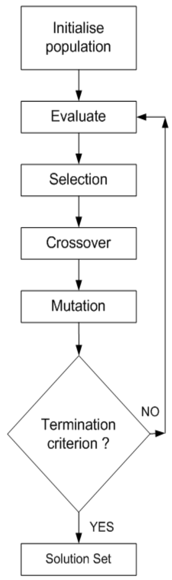

Fig8. Genetic algorithm process.

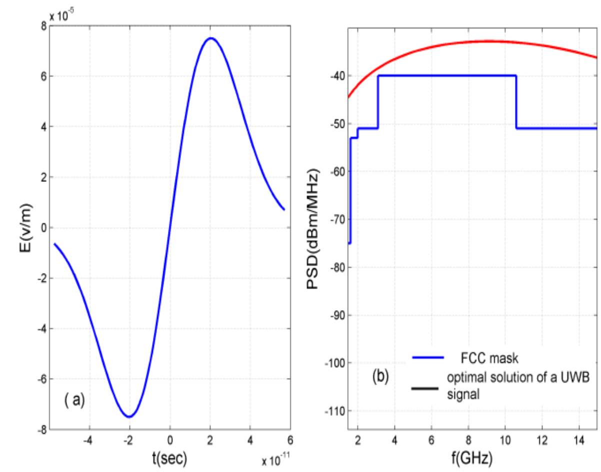

Fig9. Optimal solution of a UWB signal formed by Gaussian monocycles pulse
(a) Time domain, (b) frequency domain

4 Results

Now we will look for an optimum energy with random variables method. Then, we look at the waveform of the signal at the heart place modeled by the FDTD method.

4.1 Result of the random variable method

We looked for a three random series of central frequency, repetition frequency and amplitude under constraints indicated in preceding paragraph. The series is presented by the following tables:

TABLE 3
Random series of central frequency, repetition rate and amplitude

fc(GHz)	PRI(MHz)	A(µV)
5.25	426.5	0.429
6.00	480.0	0.419
6.50	487.0	0.402
6.75	506.0	0.3925
7.00	30.0	1.780
8.65	40.0	1.025
9.00	650.0	0.307
9.50	120.0	0.750
9. 75	870.0	0.3025
10.00	550.0	0.375

The resolution of this system provides the best solution with f = 7.8 GHz, PRI = 1.2 GHz and amplitude A = 1 µV, we also obtain a -48.2 dBm DSP (figure 9).

The following figure shows this signal pulse at the heart place

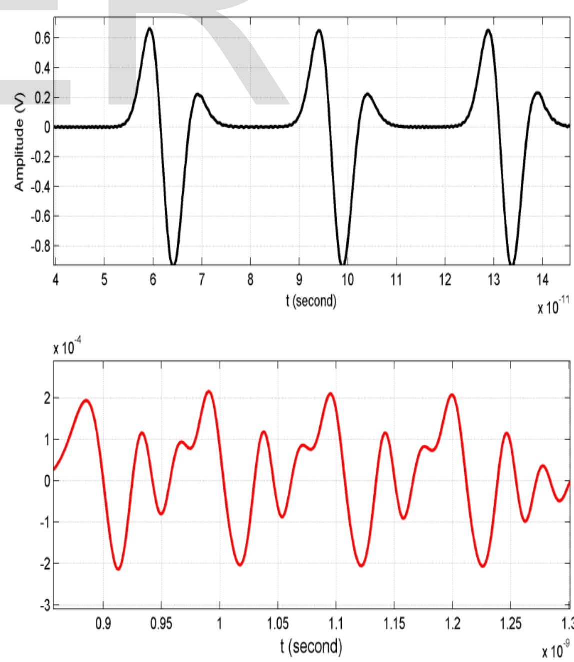

Fig10. Gaussian monocycle at source place and at heart

Figure 9 shows that the obtained solution not respected the FCC constraints. This amounts to the values of the random series itself. The lowest values may be a solution that does

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respect constraints of the FCC or the length of the random series does not lead to a real solution. Moreover, when the signal is observed at the target and the source, we note that this unicycle solutions overlap themselves. Then, these impulses are the signal, so it cannot possible to capture the heartbeat. The tables show that when one changes, the solution changes and becomes almost unchangeable if the length series exceed 50 elements.

TABLE 4
Random series of central frequency, repetition rate and amplitude

Length of random series	fc(GHz)	PRI(MHz)	Amplitude (µV)	maximum DSP (dBm)
20	7.8	1200	0.75	-32.6
25	8.2	1100	0.099	-39.7
30	6.79	587.1	0.059	-47.55
50	5.78	5.3	0.23	-51.9778
75	5.5	5.25	0.199	-51.0122
90	5.7	5.55	0.189	-51.223

Then, we need to add another constraint between the center frequency "fc" and the repetition frequency "PRI". We set the limit of this ratio to 0.025 order to separate the pulses well apart and we also imposed a limit to report "R", which is the quotient between the center frequency fc and the repetition frequency. This ratio is defined as follows

$$R = \frac{PRI}{f_c} \qquad (13)$$

4.2 Results of genetic method.

4.2.1 Problem Formulation

We want to minimize the gap between the DSP signal and the power barrier imposed by the FCC. This translates by the UWB systems EIRP barrier (maximum Energy Isotropic Radiated Power Radiated).

$$\min(DSP - (ERIP - \partial) \qquad (15)$$

Where:

∂: Gap compulsory for the EIRP to move the DSP closer to this modified barrier. under these conditions:

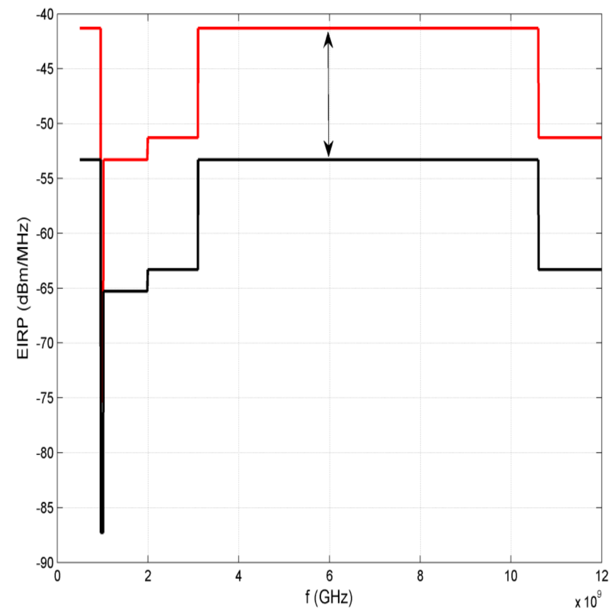

Fig11 Energy barrier imposed by the FCC and its shift

In other words, we want to approach the DSP signal to the FCC mask which means minimizing the gap between the DSP and the mask. The principle consists of:

Set a gap.

Reduce the mask of the FCC to this gap. We modify individuals selection, crossover and mutation functions.

If the fitness function is around zero, then we arrive at an optimum solution.

If not, we change individuals thanks to the operator GA.

Now, we will develop different parts of the genetic algorithm shown in Figure 8, where each party of this algorithm is represented by a deputy program or a function.

Individuals are usually the first population randomly generated. It is generated using random variables between the maximum and minimum individuals of the studied population.

We will bring the DSP signal at this location as indicated in Figure 11:

$$\begin{cases} 3.1\ GHz \le f_C \le 10.6\ GHz \\ 10^{-4} \le R < 0.025 \end{cases} \qquad (16)$$

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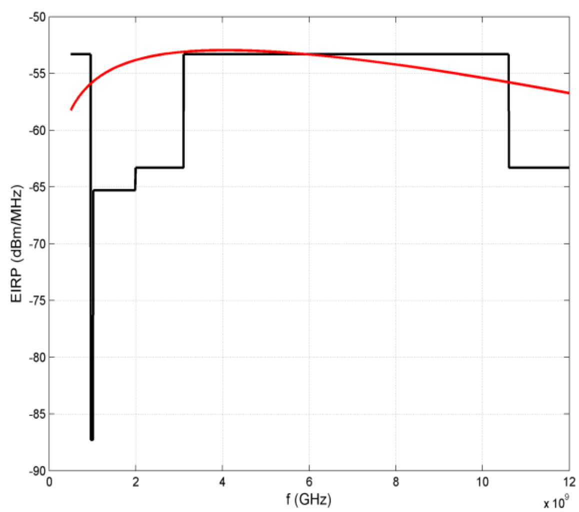

Fig12 Energy barrier imposed by the FCC and the DSP of

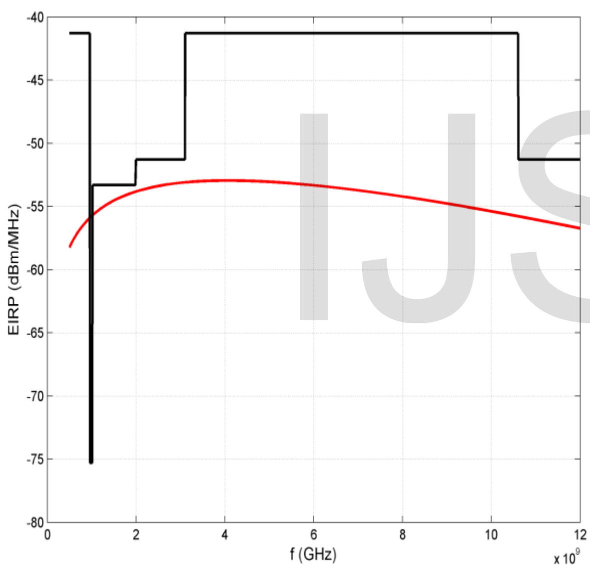

Fig13 DSP closer to the energy barrier imposed by the FCC

∂: is the loss of energy sent to the target. In applying the GA, we get optimal solution as the values shown in Table 3

TABLE 3
Optimal solution getting by GA..

fc (GHz)	PRI (MHz)	A (μV)
6.3638	6.2297	0.12851

4.3 Results of the random variable corrected method

Now, we try to correct the random variables method in the aim of validating the values obtained by the genetic method. The method has become iterative where at each step of calculating, we will correct the solution for what is under the constraints of the FCC. Generally, correction is made according to the PRI repetition frequency and the A amplitude. At each iteration, we add two corrected solutions to the random series. We will stop the process when the DSP is constant or corrections are below a threshold.
The process is explained in Figure 14.

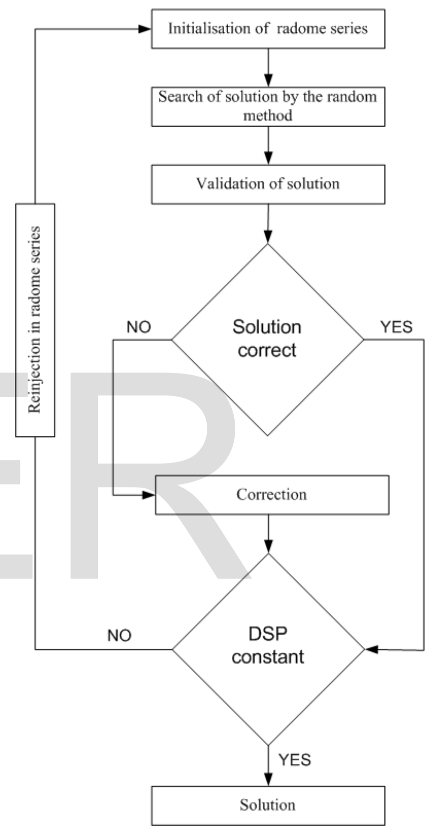

Fig 14. Random algorithm process

In applying the random variable corrected method, we get optimal solution as the values shown in Table 4

TABLE 4
Optimal solution getting random variable corrected method..

fc (GHz)	PRI (MHz)	A (μV)
5.987	6. 97	0.33851

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The DSP is closer to the maximum of energy barrier, see in figure 15

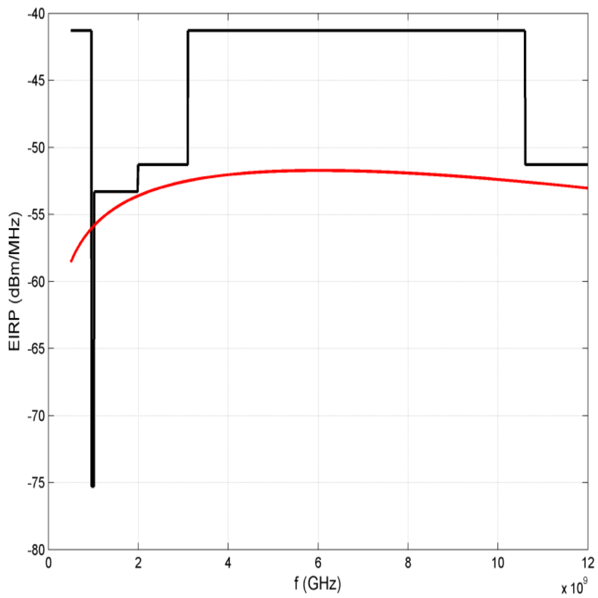

Fig15 DSP closer to the energy barrier imposed by the FCC

The following figure shows the shape of the signal at the source and at the heart. We chose the mean of the both solution (GA and random variable).

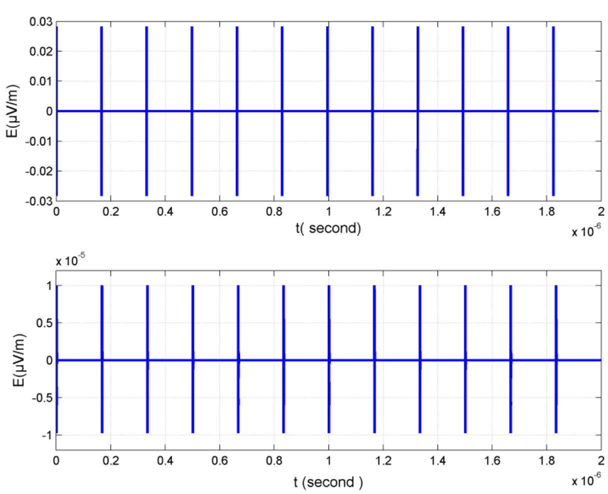

Fig16 Gaussian monocycle at heart and at source pulse.

In applying this method, we obtained the variable values shown in Table5

TABLE 5
Medium variable values of both solutions (GA and random variable)..

fc (GHz)	PRI (MHz)	A (µV)
6.2	6	0.26851

Figure 17 illustrates a zoom on the form of pulses at the heart

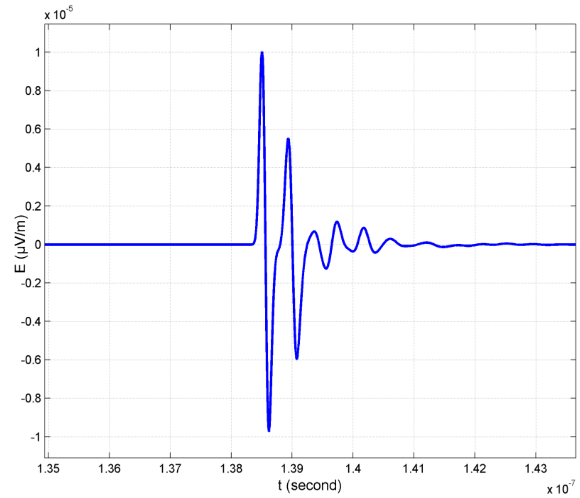

Fig17 Zoom on the form of pulses at the heart position

Figures 15 and 16 show that the pulses of electric field are well spaced. This permits the transfer to the receiving antenna of the information on the inner layers not only on time but also on the dimensions of these layers and internal movements. However, this is necessary to have time intervals medium grades to avoid duplication of answers interfaces between adjacent layers of the human body. Notice that with a 30 ps pulse width, the response signal at the heart-lung interface requires about 4 ns.

6. Conclusion

We have extracted the characteristics of an ultra-band signal to deliver maximum power to the human body while respecting the constraints of the Federal Communications Commission "FCC". To obtain maximum signal power at the target, the signal formed by monocycle Gaussian pulses must have the following characteristics: the center frequency "fc" equal to 6.2 GHz, the repetition period of "PRI" pulses equal to 6.52 MHz and a pulse amplitude "A" is 0.28 microvolts. These results are obtained by two different methods, the random variable method and the genetic algorithm method. These two methods are generally not used for optimization but we modified them a little bit so that they are adapted to our needs. For the genetic method, we try to get as close as possible to the DSP of the UWB signal of the FCC barrier. Whereas, for the random variable method, we have to converge by series to a constant optimum while adding to the random series the last solution. The values obtained by the two methods are very close and

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lead to an energy level of about -53 dBm. Energy losses from the FCC barrier limit are set at approximately 11 dBm.
That for, we note that the amplitude values are below 1µv. This amplitude is rather weak, which risks that the signal will be drowned in the noise of the propagation channel. It is therefore essential to study from the perspective of the effect of noise during the propagation of the signal in the inner layers. In addition it is very important to study the performance of the antenna so that they are adapted to our problem.

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