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Design and Analysis of a High Data Rate Transceiver using Novel Pulses for IR-UWB PLAN

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Abstract* – Personal Local Area Network (PLAN) is a communications system that provides wireless connectivity for a very large number of interactive digital devices within a limited area of about 10 m radius. The wired connectivity for the increasing number of devices that complement computer functions has become so large that wired connectivity has become prohibitive. The design and analysis of a multiple input, multiple output (MIMO) transceiver that operates at high bit rates is designed and analyzed. The system includes a novel pulse generator of extremely short pulses that comply with the spectral mask requirements of the FCC regulations for IR-UWB. Monocycle sine wave pulses or parts thereof depending on the clipping angle can be varied from 360 degrees to a few degrees. The spectral mask of the pulses may be manipulated to suit a variety of applications including UWB. The frequency range can be within the range recommended by the FCC to mitigate interference with narrow band systems. The system includes supporting circuits; low noise amplifier (LNA), and antenna etc. is capable of operating at a bit rate in the Gbps range. This PLAN overcomes interference with all existing narrowband systems including WiMAX, WLAN 802.11b and 802.11a, GPS, PCS, and surpasses existing techniques, in terms of mitigation levels and reduced complexity.

***Keywords*-UWB, PLAN, Connectivity, Gb Pulse, MIMO**

I. INTRODUCTION

The rapid increase in the use of a wide variety of inter-related digital devices require efficient, high speed inter-connectivity. The connectivity of personal local area network (PLAN) involving digital devices, subsystems, industrial, commercial, medical, military and domestic applications using ordinary wiring methods has become most inconvenient and almost impossible. Therefore, a PLAN of about 10m radius, which uses wireless connectivity, has become a necessity. Impulse Radio Ultra-Wide Band (IR-UWB) provides a plausible solution to current and future problems.

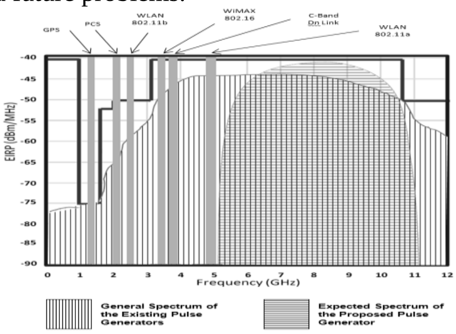

Fig. 1. Illustration for the expected spectrum of the proposed pulse generator with narrowband interference mitigation as compared with the general spectrum of the existing pulse generators.

Two key decisions are required to achieve the objective, Fig.1. The first is interference mitigation with fixed band transmission, and the second is to find technique for generating suitable pulses. The UWB technique in wireless communications is potentially the best short range wireless technology in terms of speed, power and cost. The main challenge however, is interference and compliance with FCC regulations. Although much research effort has been devoted to solve this serious problem, like notch spectrum, multi-notch, antenna directivity and direct sequence techniques etc., they are either limited to a specific band, or have limited mitigation levels. Some systems do it at the expense of reduced performance and/or increased system complexity. Much research [1, 2] focuses on Gaussian family pulses and their derivatives, as shown below.

$$x_0(t) = \frac{A}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}} \tag{1}$$

$$x_1(t) = -\frac{A \cdot t}{\sqrt{2\pi\sigma^3}} e^{-\frac{t^2}{2\sigma^2}} \tag{2}$$

$$x_2(t) = -\frac{A}{\sqrt{2\pi\sigma^3}} \left(1 - \frac{t^2}{\sigma^2}\right) e^{-\frac{t^2}{2\sigma^2}} \tag{3}$$

$$x_3(t) = -\frac{A}{\sqrt{2\pi\sigma^3}} \left(\frac{t^3}{\sigma^4} - \frac{3t}{\sigma^2}\right) e^{-\frac{t^2}{2\sigma^2}} \tag{4}$$

$$x_4(t) = -\frac{A}{\sqrt{2\pi\sigma^3}} \left(-\frac{t^4}{\sigma^6} + \frac{6t^2}{\sigma^4} - \frac{3}{\sigma^2}\right) e^{-\frac{t^2}{2\sigma^2}} \tag{5}$$

$$x_5(t) = -\frac{A}{\sqrt{2\pi\sigma^3}} \left(\frac{t^5}{\sigma^8} - \frac{10t^3}{\sigma^6} + \frac{15}{\sigma^4}\right) e^{-\frac{t^2}{2\sigma^2}} \tag{6}$$

$$x_6(t) = -\frac{A}{\sqrt{2\pi\sigma^3}} \left(-\frac{t^6}{\sigma^{10}} + \frac{15t^4}{\sigma^8} - \frac{45t^2}{\sigma^6} + \frac{15}{\sigma^4}\right) e^{-\frac{t^2}{2\sigma^2}} \tag{7}$$

$$x_7(t) = -\frac{A}{\sqrt{2\pi\sigma^3}} \left(\frac{t^7}{\sigma^{12}} - \frac{12t^5}{\sigma^{10}} + \frac{105t^3}{\sigma^8} - \frac{105t}{\sigma^6}\right) e^{-\frac{t^2}{2\sigma^2}} \tag{8}$$

where σ is the Gaussian deviation factor and A is the pulse amplitude. The paucity of research on using the monocycle sine wave pulse for UWB is related to the difficulty in designing an oscillator to generate monocycle sine wave pulse [3]. Therefore, most UWB research is based on one of the Gaussian family pulses [4]. The UWB pulses in this work based on sine wave and rectified sine wave pulses, which utilizes a much simpler and a much more effective method.

II. PLAUSIBILITY OF THE SUGGESTED SOLUTION

The required pulses are generated by a technique based on the combination of a sine wave and digital pulse. Theoretical

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analysis, simulation results and the practical measurements gave excellent agreement, which constitute the validation of the results. The novel technique presented in this paper therefore provides a better solution than all techniques published hitherto. It is simpler and more effective.

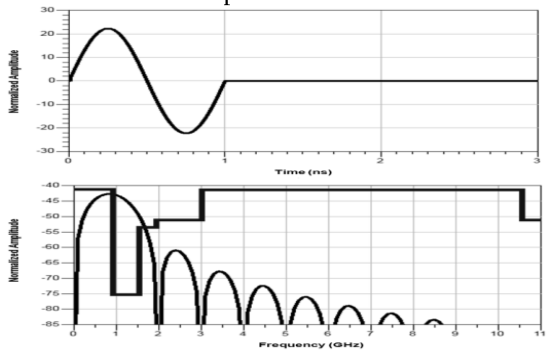

Fig. 2. The simulation results of a monocycle sine wave pulse in time and frequency domains based on sine wave source of 500 MHz.

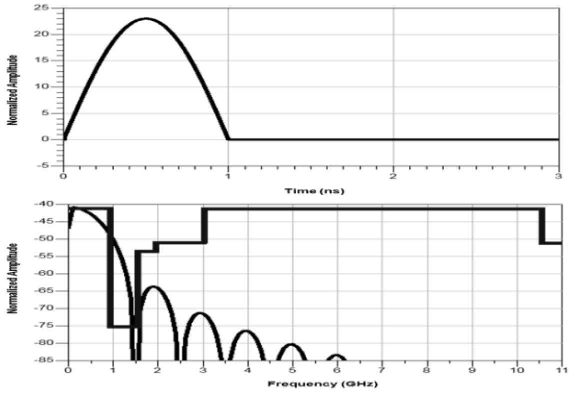

Fig. 3. The simulation results of a monocycle half wave rectified sine wave pulse in time and frequency domains based on sine wave source of 500 MHz.

Two UWB pulse generators are designed and implemented based on this pulse shaping technique. The pulse spectra in both cases comply in an excellent manner with standard spectral mask for UWB pulses. Therefore excellent mitigation is achieved with most existing narrowband systems including GPS, PCS, WiMAX, WLAN 8O2.11a and 802.11b, as indicated by the consistency of the results obtained by simulation using ADS software. See Figs. 4 and 5.

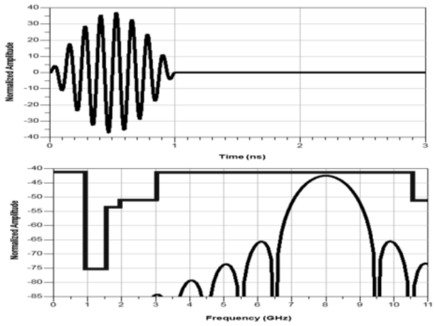

Fig. 4. The simulation results of an up-converted monocycle half wave rectified sine wave pulse in time and frequency domains, using 8 GHz center frequency and based on 500 MHz sine wave source.

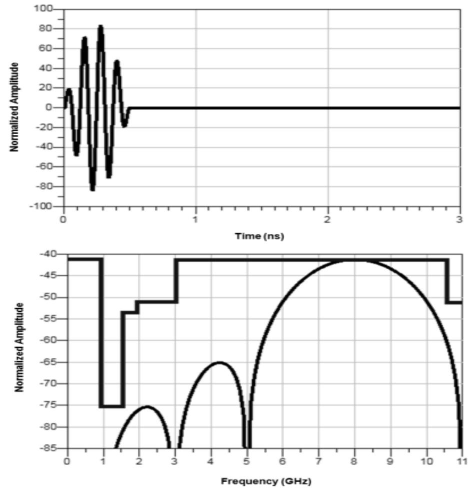

Fig. 5. The simulation results of an up-converted monocycle half wave rectified sine wave pulse in time and frequency domains, using 8 GHz center frequency and based on 1 GHz sine wave source.

The design of the pulse generating circuits is given in Figs. 6 and 7.

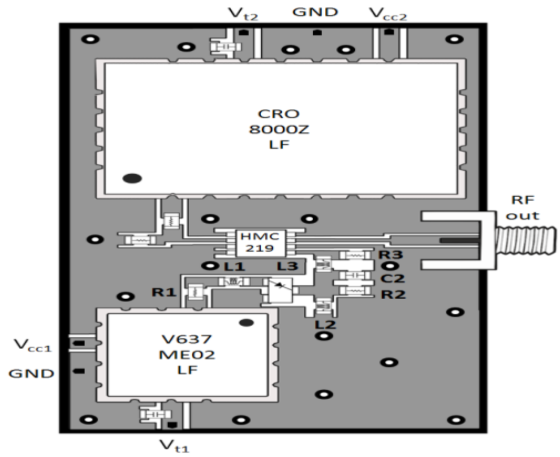

Fig. 6. The circuit layout of the designed SM-S pulse generator

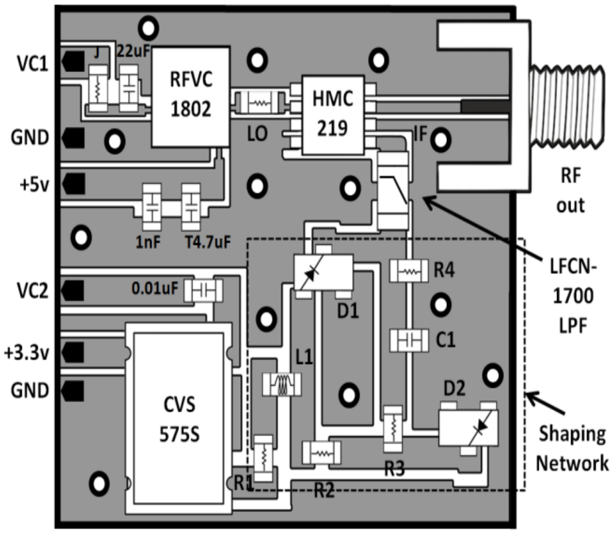

Fig. 7. The circuit layout of the designed SM-HRS pulse generator.

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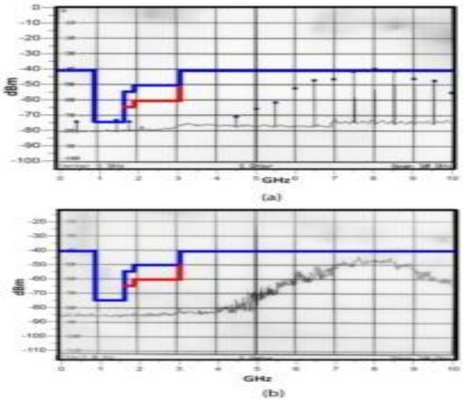

Fig. 8. The measured spectrum from 0-10 GHz for the (a) un-modulated and (b) modulated up-converted pulses.

The Tektronix MSO 4104 Mixes Signal Oscilloscope showed 27.8mV$_{pp}$ for the pulse amplitude and a period between pulses of less than 600 ps.

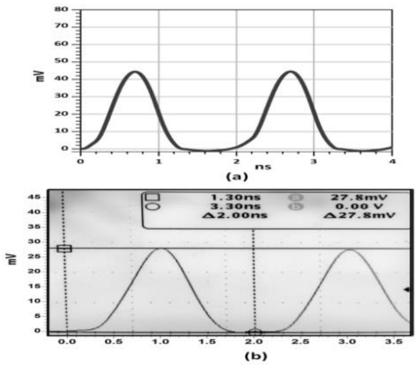

Fig. 9. The LPF output (a) simulation, (b) practical measurement.

III. HIGH BIT-RATE APPLICABILITY

The novel design was proposed for a 1-Gbps IR-UWB pulse generator [Bali 1]. The generated pulse is not just suitable for solving the problem of UWB interference with WLAN 802.11a and WiMAX systems, but no interference with any narrowband system below 3.1GHz. The spectrum of the pulse satisfies the requirements of the Federal Communication Commission (FCC) UWB indoor as well as outdoor mask. The interference mitigation on WiMAX band is less than - 80dBm/MHz. Interference on 802.11a band is avoided by adjusting a spectral notch of less than 85dBm/MHz at 5GHz. The pulse generator uses a single two ports parallel coupled micro strip line as a band pass filter (BPF). The same pulse generator can be used for Pulse Position Modulation (PPM) or On-Off Keying (OOK). Further utilization of the IR-UWB proposed pulses 4-Gbps and 6-Gbps are suggested for short range wireless communication [6]. The simple structure of the pulse generator helps to overcome the limitations of generating the two high speed systems. The pulse generator is based on two synchronized sources of 2 GHz only. The pulse generation technique supports transmission of 250ps pulses with immunity on pulse overlapping. The spectrum of the generated pulses also complies with the FCC regulations on UWB frequency mask requirements for indoor and outdoor.

A combination of two modulation schemes has been used to increase the system throughput, Bi-Phase Modulation (BPM) and On-Off Keying. More recently [7] a novel design achieved a speed of 8 Gbps with IR-UWB pulse generator for a short distance wireless communication PLAN. The proposed pulse generator is based on 250 ps pulses, which gives advantages in pulse generation and detection error reduction. The generated pulses satisfy the regulations of UWB Federal Communication Commission (FCC) indoor and outdoor masks, while the pulse amplitude is 120 mVpp. The simple and efficient pulse generator is based on using four mixers with delay units working together with synchronized train of square pulses and sine wave power sources. The designed pulse generator utilizes on-off keying (OOK) and bi-phase modulation (BPM) techniques to increase the generator throughput speed. The design has been carried out using Advanced Design System (ADS) software.

IV. PROPOSED TRANSMITTER DESIGN

Fig. 10 below shows the block diagram for the proposed transmitter.

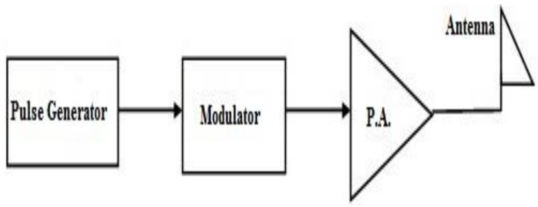

Fig. 10. The block diagram for the proposed transmitter.

From the above, the transmitter consists of 4 blocks; Pulse Generator (PG), Modulator, Power Amplifier (PA), and Antenna. Both of the PG and Modulator are explained in the previous sections, also the transmitter used the Power Amplifier (PA) for two reasons, firstly the antenna works as a power attenuator and secondly to transmit the pass-band signal to 1 m. Antenna design in ultra-wideband (UWB) systems is a major challenge. For, in contrast to conventional systems, wherein waveform distortion by the antenna is negligible, there is potentially significant waveform distortion by UWB antennas [8]. A further challenge to UWB system design is posed by mandated limits on power spectrum density, such as the FCC emission mask, so this transceiver uses the same simple monopole antenna for both transmitter and receiver that operate from 6-10.6 GHz, because the monopole antenna is a good candidate for IR-UWB that operate from 6-10.6 GHz [9]. UWB antennas act as band-pass filters [8] and [10] therefore the proposed antenna consists of a high-pass and low-pass filters with the resistance radiation (Rrad). The (Rrad) is an important parameter to reproduce the radiated waveform, furthermore, the transfer function [10]. The optimizations of the component values are made in using Advanced Design System (ADS) software. Fig. 11 below shows the schematic diagram for the proposed RLC monopole antenna with the

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antenna gain result at 0.7 (-1.54 dB) to pass frequencies from 6-10.6 GHz.

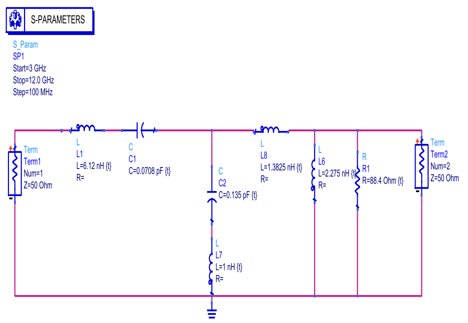

Fig. 11. Schematic diagram for the proposed RLC monopole antenna.

By simulating in a momentum software package under Advanced Design System (ADS) software, the on chip monopole antenna designed in the air layer and it operates at 8.33 GHz, then , where c is the speed of the light which = 3*10^8 m/sec^2, then the length of the antenna (L) = 36 mm and the size(S) =. The width (W) of the antenna is adjusted by the Advanced Design System (ADS) software tuner which equal to 2.4 mm. Fig. 12 shows on chip monopole antenna prototype made of copper with L=36 mm, W=2.4 mm, and S=9 mm and it placed on the air layer over the GaAs layer. The GaAs layer is assigned to transceiver design. Fig. 13 shows the antenna gain for both RLC and a prototype monopole antenna at -1.54 dB. One of the important parameters for measuring performance index of antenna is the transfer characteristic i.e. S21 between the receiving antenna and transmitting antenna. Here the transfer characteristic can be defined as the ratio of power given to the input of the antenna from the transmitter side to the power received by the antenna at the receiver side. If it was considered the radiation efficiency, the equation of S21 can be written as follows [8].

$$S_{21} = -S_{11} + \eta_t \text{ -} \qquad (1)$$

Where antenna transmitting efficiency and antenna receiving efficiency respectively. *PL* is a path loss. If both the transmitter and receiver antennas are identical, their characteristics are same i.e. $t = r$ and the above equation (1) for S21 becomes

(2)

The Path Loss (*PL*) can be calculated from equation [8] below

$$PL \qquad (3)$$

Where *fc* is the central frequency = 8.33 GHz with antenna gain, G = 1- |(S11)*(S22)| = 1-|(S11)|^2= 0.7 as a factor ,that mean G= 10 log (0.7)= -1.54 db, *d* is the distance between transmitting antenna and receiving antenna, that will be assumed equal to 1 m, and *c* is the speed of the light= 8*10^8 m/sec., then *PL* 51 db. From equation (2), S21=2*G-PL= -3-51=-54dB. Therefore, the required S21 within 1 m distance comes out to be -54 dB.

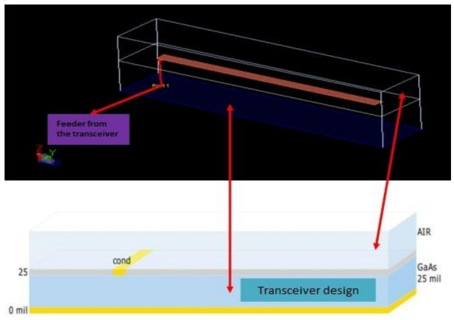

Fig. 12. On chip monopole antenna prototype with L=36 mm, W=2.4 mm, and S=9 mm on the top of GaAS layer.

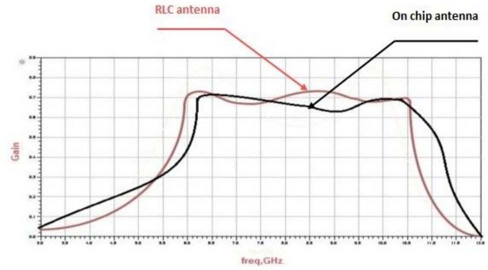

Fig. 13. Antenna gain for both RLC and a prototype monopole antenna at -1.54 dB to pass frequencies from 6-10.6 GHz.

Fig.14. Below shows the antenna output pulse in time and frequency domains at center frequency 8.33GHz to pass frequencies from 6-10.6 GHZ.

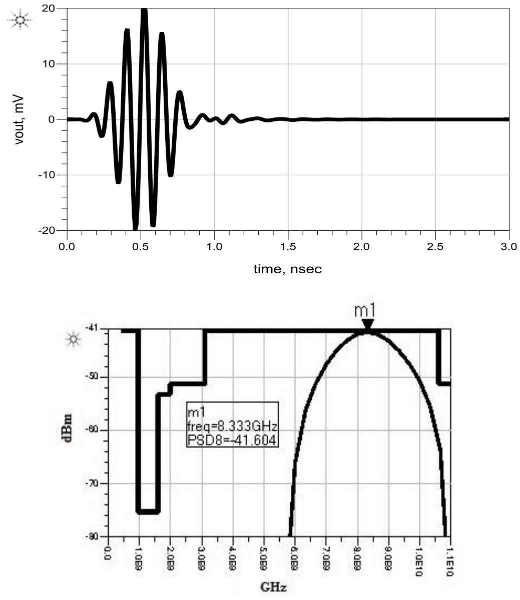

Fig. 14. Antenna output pulse in time and frequency domains.

V. MULTI-USER MIMO SCHEME

An up-converted pulse with 4.5 GHz is shown in Fig. 15. A 9 GHz up-converted pulse is shown in Fig.16. These pulses are of 1ns width and about 110mV$_{pp}$ amplitude. Furthermore they are of a 4.5 GHz bandwidth at 80 dBm.

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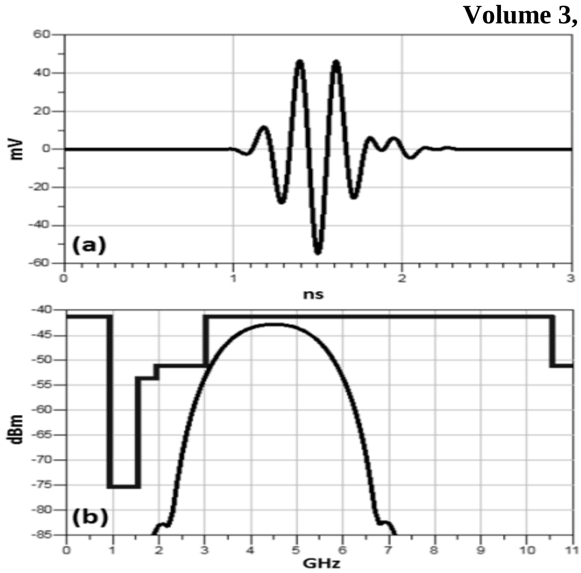

Fig. 15. The up-converted pulse with 4.5 GHz in (a) time and (b) frequency domains.

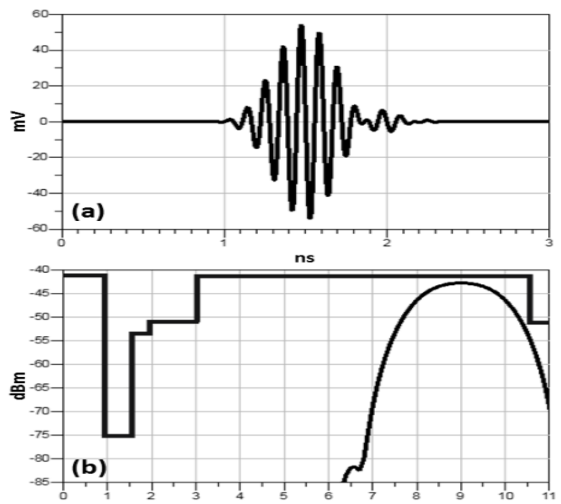

Fig. 16. The up-converted pulse with 9.0 GHz in (a) time and (b) frequency domains.

The model can deliver 1 Gbps by using only one mixer. However, it can deliver 2 Gbps by adding Bi-Phase Modulation (BPM) technique. Two pulses with a phase shift of 180^{o} are possible with the positive and negative half cycles. Using a delay unit with BPM is part of a pulse position phase modulation (PPPM) scheme, see Fig. 17 below.

TABLE 2. Output configuration to deliver 2 Gbps using FM PG-Model with BPM technique.

2-bits of Data Every 1 ns	Decision Circuit Output
00	+ve pulse @ 4.5
01	+ve pulse @ 9.0
10	-ve pulse @ 4.5
11	-ve pulse @ 9.0

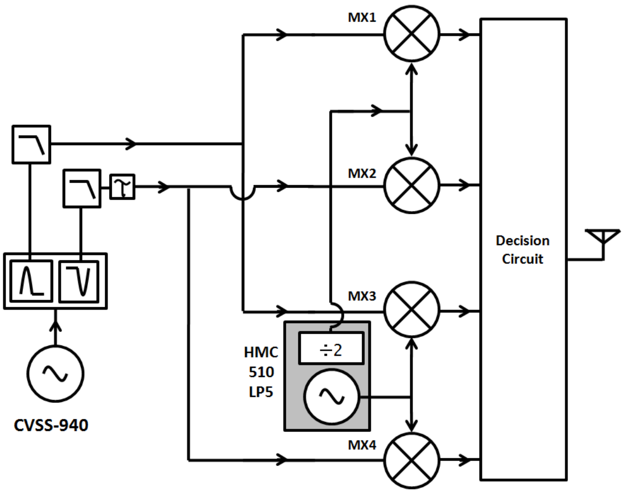

Fig. 17. FM Pulse Generator model structure with BPM technique.

VI. MIMO PULSE GENERATER MODEL

The model shows the applicability and validity of using monocycle half rectified sine wave pulse generation with MIMO schemes. The technique is applicable to a variety of purposes including antenna directivity [11][12][13] and for Radar MIMO technique to improve near field high resolution imaging [14]. The model employs three working frequencies to increase throughput. If improved efficiency is required in a noisy channel, the signal can be sent via three different antennas using three different frequencies, to improve SNR as shown in Fig.18 below.

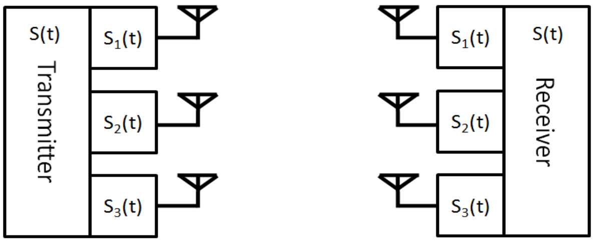

Fig. 18. A system with MIMO technique

The FM PG-Model is structured on three parts; the half rectified sine wave generator, the stepped impedance low pass micro strip filter which is lump designed based on Bessel filter. A frequency shifting stage is an up-converter that shifts the centre of the spectrum of the generated pulses to 3.1-10.6 GHz.

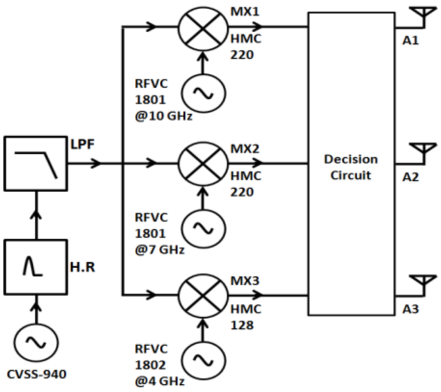

Fig. 19. MIMO PG-Model structure

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As shown in Fig. 19, three up-converter mixers are used for three different frequencies simultaneously and separately. The main sine wave signal is derived from a crystal controlled 250MHz VCO with a 3.3V true sine wave. The MIMO can be used for spatial multiplexing, where three bits can be sent every 4ns separately at three different frequencies of 4, 7 and, 10GHz. In addition, the model operates with two antennas 7 and 10 GHz with a mitigation level of -85 dBm/MHz between 0 and 5 GHz. The throughput will be 500Mbps. This configuration triples the system efficiency by improving the SNR.

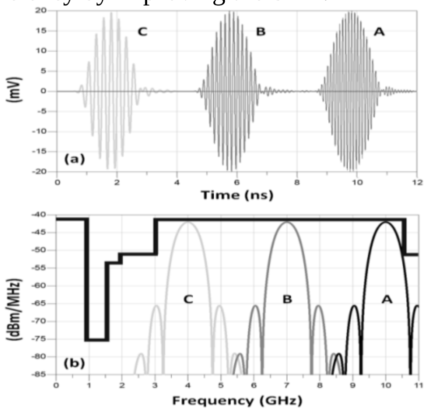

Fig. 20. The pulses after up-converting to 10, 7 and 4 GHz; A, B and C respectively in time domain (a) and in the frequency domain (b).

Different modulation techniques have been used with UWB systems, with the possibility of using different types of pulse generators to examine its impact on system performance. The PPPM model is a novel technique which achieves an 8 Gbps IR-UWB.

VII. CONCLUSION

A number of novel techniques have been developed to cater for extremely fast digital connectivity. A number of systems have been analyzed theoretically that solve the mitigation problems associated with the interference of UWB pulse spectra with fixed frequency transmissions. The theoretical models have been validated by practical implementation. Actual measurements performed on circuits which were executed based on the theoretical models gave excellent agreement with calculated values. The spectral mask and power level restrictions imposed by the FCC have all been met with unprecedented results. Some novel modulation techniques such as the PPPM have been introduced, which can be useful in a variety of applications other than personal local area network (PLAN) which depend on the UWB technology. The results of the various investigations indicate that the design of the various novel systems can be readily developed for commercial applications; hence an application of a multi facetted patent has been filed.

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