A MODEL FOR NARROWBAND INTERFERENCE CONTROL IN ULTRA-WIDEBAND (UWB) INDOOR WIRELESS NETWORKS

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DECLARATION

I declare that this dissertation has been composed by me and that the work has not been published or submitted elsewhere for any other degree or professional qualification. I confirm that the work submitted is my own, and thus contain no material written or published by other people except where due reference is made and author duly acknowledged.

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I do hereby confirm that we have examined the master's dissertation of

Denis Onyango Omuko

And have certified that all revisions that the dissertation panel and examiners recommended have been adequately addressed.

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ABSTRACT

Ultra-wideband (UWB) also known as digital pulse wireless is a wireless technology for transmitting large amount of digital data over a wide spectrum frequency bands with low power over short distances.

Ultra-wideband systems cannot only carry a huge amount of data over distance up to 33 feet (10 meters) at low power (less than 0.5mw), but has the ability to carry signals through doors and other obstacles that tend to reflect signals at more limited bandwidth and higher powers (Rouse, June 2008).

With the revitalization of the UWB technology, the common Wi-Fi technology faces a blatant threat of being surpassed in the near future (Shaik, 2012).

The spreading of the signal over a wide frequency band achieves low spectral density which minimizes interference to the existing communication in the same spectrum. However, since UWB occupies a very wide frequency band, it is forced to coexist with numerous powerful licensed communication systems transmitting in the same band. The interference caused by these systems may complicate or even block the UWB communications (Ben Wilmholff, February 25, 2015). Hence a need arises to combat these interferences in the UWB systems to realize its benefits.

ACKNOWLEDGEMENT

Coming up with such a research is in vain without the support of many others. I therefore would like to greatly acknowledge and thank the enormous encouragement and support of my thesis supervisors for their guidance and assistance on many technical matters.

I would in a special way like to thank my wife, Sophia, sons, Vincent and Pachomius, for providing me the motivation and space to complete the same and above all many thanks to the almighty God.

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ABBREVIATIONS

AWGN- Additive White Gaussian Noise

ADSL- Asynchronous Digital Subscriber

ADC- Analog-to-Digital Converter

BPF- Band Pass Filter

BSF- Band Stop Filter

CDMA- Code Division Multiple Access

CPU- Central Processing Unit

CMOS- Complementary Metal Oxide Semiconductor

dB- Decibel

dBm- Decibel milliwatt

DS-CDMA- Direct Sequence Code Division Multiple Access

EHF- Extremely High Frequency

EMC- Electro Magnetic Compatibility

FCC- Federal Communications Commission

FFT- Fast Fourier Transform

GPS- Global Positioning Systems

GHz- GigaHertz

HDR- High Data Rate

HF- High Frequency

IEEE- Institute of Electrical and Electronics Engineering

ISM- Industrial Scientific and Medical

IFFT- Inverse Fast Fourier Transform

LAN- Local Area Network

LDR- Low Data Rate

LPF- Low Pass Filter

LNA- Low Noise Amplifier

LOS- Line of Site

MB-OFDM- Multi Band Orthogonal Frequency Division Multiplexing

MHz- Mega Hertz

MF- Medium Frequency

MPC- Multi Path Components

MT- Mobile Terminal

mW- Milliwatt

MMSE- Minimum Mean Square Error

MPSK- M-ary Phase Shift Keying

NBI- Narrow Band Interference

NLOS- Non Line of site

nW- Nanowatt

NIC- Network Interface Card

OFDM- Orthogonal Frequency Division Multiplexing

PC- Personal Computer

PCS- Personal Communication Service

PDA- Personal Digital Assistant

PSD- Power Spectral Density

PCB- Printed Circuit Board

PCI- Peripheral Component Interconnect

Pw- Pico Watt

RF- Radio Frequency

SIR- Signal to Interference Ratio

DSR- Design Science Research

SHF- Supper High Frequency

SAW- Surface Acoustic Wave

SQNR- Signal-to-Quantization-Noise Ratio

TH- Time Hopping

UWB - Ultra-Wide band

UNII- Unlicensed National Information Infrastructure

UHF- Ultra High Frequency

VGA- Variable Gain Amplifier

VLF-Very Low Frequency

VHF- Very High Frequency

WBAN- Wireless Body Area Networks

WLAN- Wireless Local Area Network

Wi-Fi- Wireless Fidelity

Chapter 1: INTRODUCTION

Narrowband, as an interferer signal in UWB, describes telecommunication network and services that carries information in a radio frequency spectrum (RF), which is divided within ranges from very low frequency (VLF) to extremely very high frequency (VHF) in manner that each band has a defined upper and lower frequency limits.

Ultra-wideband (UWB) has emerged as a tempting solution for wireless applications requiring very high data rates, low power, robustness to multipath fading, positioning capability and low cost circuitry. UWB technology is attracting much attention as an indoor short-range high-speed wireless communication. One of the most exciting characteristics of UWB is that its bandwidth is over 110 Mbps (up to 480 Mbps) which can satisfy most of the multimedia applications such as audio and video delivery in home networking and it can also act as a wireless cable replacement of high speed serial bus such as USB 2.0 and LAN IEEE1394 (Plastic Optical Fibre). Multi nearby transmissions can also be supported in UWB networks using an appropriate code assignment mechanism (Giuliano Manzi, May 2009).

This technology is assigned the frequency band of 3.1 GHz to 10.6 GHz (a band more than 7 GHz wide) by the Federal Communications Commission (FCC), where it is permitted to coexist with other licensed and unlicensed communication systems without requiring a license (Std., 2003). Each radio channel can have a bandwidth of more than 500 MHz depending upon its center frequency. The use of UWB (range of 3.1 – 10.6 GHz) was deregulated in the United State of America (USA) in the early 2002 by the Federal Communication Commission (FCC) for unlicensed use of short-distance. This de-regulation is with a restriction that the average transmitted power of the UWB signal does not exceed -41.3 dBm/MHz, which is of a very low power spectral density. This is to mean that due to such a large signal bandwidth, the FCC has put severe broadcast power restriction. By doing so, UWB devices can make use of extremely wide frequency band while emitting very less amount of energy. In response, the IEEE formed the 802.15.3a working group and began accepting propasals on how to best utilise this particular bandwidth (Std., 2003).

Two modulation formats emerged to becoming the 802.15.3a standard. One of these is Direct-Sequence Code Division Multiple access (DS-CDMA) (R. Fisher, 2004), and is based on technology similar to Personal Communication Service (PCS) cellular systems. The second is Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) (A. Batra, 2004.), and is an extension to the modulation format used in Asynchronous Digital Subscriber Lines (ADSL) and 802.11a Wireless Local area Networks (WLAN).

This work would be based on the MB-OFDM since it seems to be more popular of the two modulation formats. The technology is more appropiate in terms of coexistence because of its unique feature that it can easily turn off some subcarrier frequencies which may interfere, or to be interfered with other systems.This technology has already gained the 75% industry approval required for becoming the 802.15.3a standard (A. Batra, 2004). To combat the interference in the Multi-band OFDM (MB-OFDM) UWB systems, an analog notch filter is designed to be included in the receive chain.

	UWB	**Wi-Fi**
IEEE Standard	802.15.3	802.11a/b/g
Frequency Bandwidth	3.1 GHz – 10.6GHz	2.4 GHz, 5GHz
Maximum Signal Rate	110 Mb/s	54Mb/s
Nominal Range	10m	100m
Transmitter Power	-41.3dBm/MHz	15-20dBm
Channel Bandwidth	500MHz -7.5GHz	22MHz
Latency	1.8ms	17ms
Cost	Low	Comparatively Low

Table 1: Comparison of Ultra-Wide Band and Wi-Fi Technology (Giuliano Manzi, May 2009)

1.1. Background of the problem

Due to the restrain on the transmission power level of the UWB, the UWB systems would unavoidably suffer from the interference caused by the coexisting systems, which are narrowband relative to UWB and transmit at much higher power levels. This narrowband interference can sometimes be so effective that the UWB communications is totally prevented.

Therefore the suppression of this narrowband interference is of paramount importance in UWB systems (Chugg, Nov. 2002).

In dealing with NBI in UWB systems, it will be considered that there are some potential interferers with predetermined center frequencies and bandwidths. These interferers are the narrowband systems operating in the frequency band of 3.1 GHz to 10.6 GHz, and the most effective one among them is the IEEE 802.11a.

1.2. Problem statement

Due to the restrain on the transmission power level of the UWB, the UWB systems would unavoidably suffer from the interference caused by the coexisting systems, which are narrowband relative to UWB and transmit at much higher power levels. This narrowband interference can sometimes be so effective that the UWB communications is totally prevented. Therefore the suppression of this narrowband interference is of paramount importance in UWB systems for its effective applications.

Considering the attractive characteristics of the UWB technologies as the next potential short range wireless technology, robustness against jamming is very important as also a large number of electrical devices emitting narrowband noise are usually found in home and office environments where much of this service would be applicable, as well as interfering signals from wireless services operating in sections of the UWB bandwidth.

1.3. Objective of the research

1.3.1. Main objective

The main objective of this research is to develop a model for narrowband interference control in Ultra-Wideband (UWB) indoor wireless networks.

1.3.2. Specific objectives

i. Identify and define the narrowband interferers in UWB networks.

ii. Design and develop a model for the narrowband interference control measures to the Ultra-wideband indoor wireless network by use of notch filters.

iii. Implement the developed model on the applications of free from narrowband interference UWB signals indoors.

iv. Test and validate the proposed model.

1.4. Research Questions

i. Are there any of interferences caused by narrowband signals and that would impact the operation of UWB networks?

ii. What processes can be used to design and develop a model that would mitigate the narrowband interference in UWB indoor wireless networks if found in (i)?

iii. Is the developed model implementable in the applications of a free from narrowband interference UWB signals indoors?

iv. Can the model be tested and validated for the proposed objective?

1.5. Significance of the study

The significance of this research is to provide data on interference by narrowband signals to the UWB signals indoors.

The results can be useful for various growing demands for wireless applications requiring very high data rates, low power, robustness to multipath fading and low costs wireless systems compared to the common Wi-Fi technology.

1.6. Motivation on the research

UWB communications offers a radically different approach to wireless communication compared to conventional narrowband, promising very high data rates along with low cost hardware and low power consumption. High data rate applications of UWB wireless technology have drawn much attention, since many of the applications are suited to the consumer market (Giuliano Manzi, 2009).

1.7. Scope and limitation

The research is intend to identify narrowband interferers and levels in the UWB signal band, design and implement corrective measures to correct the same for effective application of UWB signals within the covered bandwidth indoors.

Because of the time line and the construction cost of the physical design model, will only use simulation techniques to implement and carry out the researched and suggested tests on the designed circuits to ensure that the required results qualify the design.

Chapter 2: LITERATURE REVIEW

2.1. Frequency bands, Frequency ranges, and Allocations

2.1.1. Frequency bands

In telecommunication, a frequency band is a specific range of frequencies in the radio frequency (RF) spectrum, which is divided among ranges from very low frequencies (VLF) to extremely high frequencies (EHF). Each band has a defined upper and lower frequency limit (Techtarget, 2016).

A frequency spectrum is a scientific method of plotting and classifying electromagnetic waves as they occur in space and in the everyday environment (Kinsellagh, 2016).

2.1.2. Frequency ranges and Allocations

Very low frequencies (VLF) range from 3 to 30 Kilohertz (kHz). Time signals and standard frequencies are among the users of this band.

Low frequencies (LF) range from 30 to 300 kHz. Fixed, maritime mobile and navigational systems and radio broadcasting are among the users of this band.

Medium frequencies (MF) range from 300 to 3000 kHz. Land, maritime mobile and radio broadcasting are among the users of this band.

High frequencies (HF), also called shortwaves, range from 3 to 30 megahertz (MHz). Fixed, mobile, aeronautical and marine mobile, amateur radio and radio broadcasting are among the users of this band (Management, 2011).

Very high frequencies (VHF) range from 30 to 300 MHz. Fixed, mobile, aeronautical and marine mobile, amateur radio, television and radio broadcasting, and radio navigation are among the users of this band.

Ultra-high frequencies (UHF) range from 300 to 3000 MHz. Fixed, mobile, aeronautical and marine mobile, amateur radio, television, radio navigation and location, meteorological, and space and satellite communication are among the users of this band.

Super high frequencies (SHF) range from 3 to 30 gigahertz (GHz). Fixed, mobile, radio navigation and location, and space and satellite communication are among the users of this band.

Extremely high frequencies (EHF) range from 30 to 300 GHz. Amateur radio, satellite, and earth space exploration are among the users of this band.

2.1.3. UWB signal

This is a radio technology pioneered by Robert A. Scholtz and others that can use a very low energy level for short-range, high-bandwidth communications over a large portion of the radio spectrum (Scholtz, 2011).

According to (Kinsellagh, 2016; FCC, Sept. 1, 1998; Department of Electrical Engineers, 15 February 2011) the ultra-wideband signal falls in the super high frequency range with the allocation of 3.1 to 10.6 GHz.

UWB radio is a field of research that is old and new at the same time. The first UWB signals were generated in experiments by Hertz in 1887, in which he generated sparks and radiated them via wide-band loaded dipoles. At that time, short, wide-band pulses were the easiest waveforms to generate. As time went on, the emphasis of communications systems shifted to narrow band carrier-based (tuned) systems, which were easier to multiplex with the technology available at that time. It was only in 1990s that the improvements in digital signal processing, and the invention and investigation of time-hopping (TH) impulse radio, revived interest (Scholtz, 1998) (Scholtz, 2000).

2.1.4. Features of UWB

- High data rate transmission

  Currently UWB systems can support more than 500Mbps data transmission within 10m, this enables various new services and applications.

- Fading robustness

  UWB systems are immune to multipath fading and are capable of resolving multipath components (MPCs) even in dense multipath environments, where resolvable paths can be combined to reduce the fading margin and enhance system performance.

- Security

  UWB systems operate below the noise floor thus are therefore inherently covert and extremely difficult for unintended users to detect.

- Low loss penetration

  UWB systems can penetrate obstacles and thus operate under both line-of-site (LOS) and non-LOS (NLOS) conditions.

- High precision ranging

  UWB systems have good time-domain resolution and can promise sub-centimeter resolution capability for location and tracking applications.

- Low power spectral density

  UWB systems have low power spectral density that allows them to coexist with other services such as cellular systems, wireless local area networks (WLAN), global positioning systems (GPS) etc.

- Single chip architecture

  UWB systems can be implemented nearly all-digitally with small-size, low cost and low power on single chip architecture (e.g. CMOS) since the RF carrier can be eliminated. Such architecture is essential for handling devices such as a mobile terminal (MT).

- Scalability

  UWB systems are very flexible because their common architecture is software re-defined so that it can dynamically trade-off high data throughput for range (Saji, 2016).

2.2. Applications of UWB Technology

2.2.1. Low Data Rate (LDR)(IEEE 802.15.4a)

The use of very short pulses in impulse radio transmission, and careful signal and architecture design, facilitate the design of very simple transmitters, permitting extreme low energy consumption and thus long-life battery-operated devices, which are mainly, used in low data rate networks with low duty cycle (J Walko, Dec/Jan 2003/4B.).

The ability to carry signals through doors and other obstacles that tend to reflect signals at more limited bandwidth and higher powers qualifies UWB technology to be applicable to surveillance and operation in areas difficult to access by human such as in military operation where detection of human target through wall is of interest, hostage rescue situations through access of unknown building layout together with presence of armed persons, disaster search and rescue operations such as people trapped under building debris during earthquake, explosion or fire (Department of Electrical Engineers, 15 February 2011).

2.2.2. High Data Rate (HDR) (IEEE 802.15.3a)

High data rate applications of UWB wireless technology have initially drawn much attention, since many of the applications are suited to the consumer market. UWB also find its application in the Wireless Personal Area Networks (WPAN) under the IEEE standard 802.15.3 for high data rate (20Mbit/s or greater) (Ben Wilmholff, February 25, 2015).

Hence commercial interest in technology development, standards and regulation is very high.

The very definition of UWB – a bandwidth exceeding 500MHz (for carrier frequencies above 2.4GHz) and extremely low power spectral density (75nW/MHz between 3.1 – 10.6GHz, according to FCC rules), makes UWB the perfect candidate technology for this kinds of scenarios. Therefore the main application areas include;

- Internet Access and multimedia services: Regardless of the envisioned environment (home, office, hot spot), very high data rates (> 1Gbits/s) have to be provided – either due to peak data rates, high number of users, or both.
- Wireless peripheral interfaces: A growing number of devices (laptop, mobile phone, Personal Digital Assistance, handset, etc.) are employed by users to organize themselves in their daily life. The required data exchange is expected to happen as conveniently as possible or even automatically. Standardized wireless interconnection is highly desirable to replace cables and proprietary plugs. It has to be emphasized, however, that wireless solutions in this

context will be attractive mainly for battery-powered devices without the need for an external power supply.

- Location based services: To supply the user with the information he/she currently needs, at any place and any time (e.g. location aware services in museums or at exhibitions), the users' position has to be accurately measured. UWB techniques may be used to accommodate positioning techniques and data transmission in a single system for indoor and outdoor operation.

2.2.3. Home Networking and Home Electronics

It is thought that many electronics manufacturers are investigating UWB as televisions, DVD players, camcorders, and audio systems, which would remove some of the wiring clutter in the living room. This is particularly important when we consider the bit rate needed for high-definition television that is in excess of 30Mbps over a distance (Saji, 2016).

2.2.4. Wireless Body Area Networks (WBAN)

Due to the proposed energy efficient operation of UWB, battery driven handheld equipment is feasible, making it perfectly suitable for medical supervision. Moreover, UWB signals are inherent robust against jamming, offering a high degree of reliability, which will be necessary to provide accurate patient health information and reliable transmission of data in a highly obstructed environment. The possibility to process and transmit a large amount of data and transfer vital information using UWB wireless body area networks would enable tele-medicine to be the solution for future medical treatment of certain conditions.

2.3. Narrowband Interference in UWB

Ultra-Wideband (UWB) radio signals have characteristics that are different from conventional radios. Of interest is the ability to spread the transmission power over a sufficiently wide bandwidth to make the signal appear as noise to a narrowband receiver, while still being able to transmit very high data rates over short distances. “Narrowband” may actually mean 20 MHZ wide.

MB-OFDM for UWB communication was developed to coexist with current narrowband communication standards. The OFDM sub-bands are located such that interferences from IEEE 802.15.1, 802.11b, 802.11a and 802.15.4 are out of band interferences, and can be adequately suppressed by the SAW and low pass filters. Though, interferences due to unintentional radiation of electronic devices may lie within the UWB bandwidth.

The huge bandwidth and low transmit power of the UWB systems makes the systems prone to radio interference that could degrade its receiver performance. The interference in UWB can be categorized into to two categories, Out-of-band (OOB) and In-band. OOB interference sources include microwave oven and existing communication standards, such as WLAN and Wi-Fi. These interference sources can be attenuated with RF surface acoustic wave (SAW) and baseband low pass filtering without affecting the UWB data because their frequencies are not within the UWB bandwidth. On the other hand the problem of in-band is interference is not well defined. This is partially due to the fact that sources of in-band interference have not been explored to the extent of the OOB interference sources.   There exist many potential interference sources within the UWB bandwidth that could hinder UWB communication. These range from computer components to common household devices such as electric shavers and hair dryers

(Myricom Inc., 2004). While the emission levels of any class-B compatible electronic device could legally have power levels of up to -41.3 dBm/MHz, those that are closer to a potential UWB receiver, such as computer components, possess a higher probability for degrading UWB receiver performance. Having not been fully demonstrated as a problem, even less research has been focused on a solution for in-band narrow-band interference (NBI) (Giuliano Manzi, May 2009).

2.3.1. Potential In-Band NBI Sources

The Electro-magnetic compatibility (EMC) reports submitted to the FCC provides good sources for finding out what types of interference a UWB receiver might expect. For example when we look into the EMC report provided to the FCC in 2004, radiation levels measured of a Local Area Network (LAN) Network Interface Card (NIC) indicate emission of -49.8 dBm at 3.75 GHz (Inc., 2004). In a separate report, emission levels of -44.3dBm at 3.75 GHz were measured for LAN switch (Inc., 2004). The former being a PCI card for a personal computer (PC) that could reside within a few centimeters of a UWB transceiver antenna. The latter is self-enclosed, but could still likely be placed near a PC, and hence, near a receiver. The centre frequency in both cases is 3.75 GHz, which lies directly within the UWB bandwidth.

In the cases of LAN NICs, LAN switches, and motherboards, the radiations are likely due to harmonics of the operating frequency.In CPUs, the fundamental frequency lies directly within the UWB spectrum and could be expected to provide high emission levels. Beyond personal computers, it is also necessary to examine the radiation levels of consumer electronics which may house a UWB transceiver, such as digital cameras, cell phones, and PDAs.

Table 1 provides a summary of some of the potential interference sources found in EMC test reports provided to the FCC. The emission measurements were taken with the device under test inside a shielded PC chassis. Typical casings are known to attenuate emissions by greater than 25 dB (Dirjish, 2003). Assuming one implemetation of a UWB tranceiver is marketed as a PCI peripheral, which is located inside the PC tower, these signals will couple to the receiver through the UWB packaging and circuit board.

Source	f_{int}	P_{int}
LAN NIC	3.75 GHz	-49.8 dBm
LAN Switches	3.75 GHz	-44.3 dBm
Motherboard	1.9 GHz	-42.7dBm
PDA	1.87 GHz	-43.9 dBm

Table 2: Potential interference sources

2.4. Design and control measures already existing and their weaknesses

Narrowband interference is not a resent problem. For example in other wideband systems that use wideband modulation formats, such as spread-spectrum code division multiple access (CDMA), narrowband interference is partially handled with the processing gain, and by employing interference cancellation techniques including notch filtering, predictive techniques, minimum mean square error (MMSE) detectors, and transform domain techniques (Letaif, 2003).

Some of the problems with these digital techniques come as a result of non-idealities in the analog front end of the filters. Which include amplitude clipping due to finite dynamic range and decreased Signal-to-Quantization-Noise Ratio (SQNR) as a result of finite precision of the Analog to Digital converter (ADC). Also it is important to note that in this carrier modulated wideband systems, the received signal, through the above process is down-converted to the baseband and sampled above Nyquist rate which allows it to be processed digitally. However, the UWB signal, being already in the baseband, cannot be sampled at the Nyquist rate with the existing technology. Therefore, the numerous narrowband interference suppression techniques proposed for other wideband systems, which can be realized by means of advanced signal processing methods, are not directly applicable to UWB systems (Sugiura, 2010).

To reduce these effects, interference needs to be reduced before the signal enters the digital domain. In (R. Pasand, 2004), a UWB receiver based on analog filter banks was proposed to suppress NBI. However, the analog power consumption and complexity of such a system are very high, since as many as 16 parallel filters and data converters were used in that work.

In this work, a single programmable analog notch filter is included in the base-band receive chain to reduce NBI before the signal is quantized. The filter is optimally placed after the baseband lowpass filter (LPF), and before the variable gain amplifier (VGA). Placing the notch filter after the LPF reduces its need to handle out of band interference, and placing it before the VGA reduces its linearity requirement.

2.4.1. Interference impact to the UWB networks

It is evident that in-band NBI is a pressing problem in the UWB systems that, if left ignored, could hinder transceiver performance. Because of the restrain on the transmission power level of the UWB, the UWB systems would suffer from the interferences caused by the coexisting narrowband systems relative to UWB and transmit at much higher power levels. This narrowband interference tends to block the UWB communications due to the effects on the quantization noise in the analog-to-digital converter (ADC), timing and carrier acquisition of the UWB network (K. Shi, 2007).

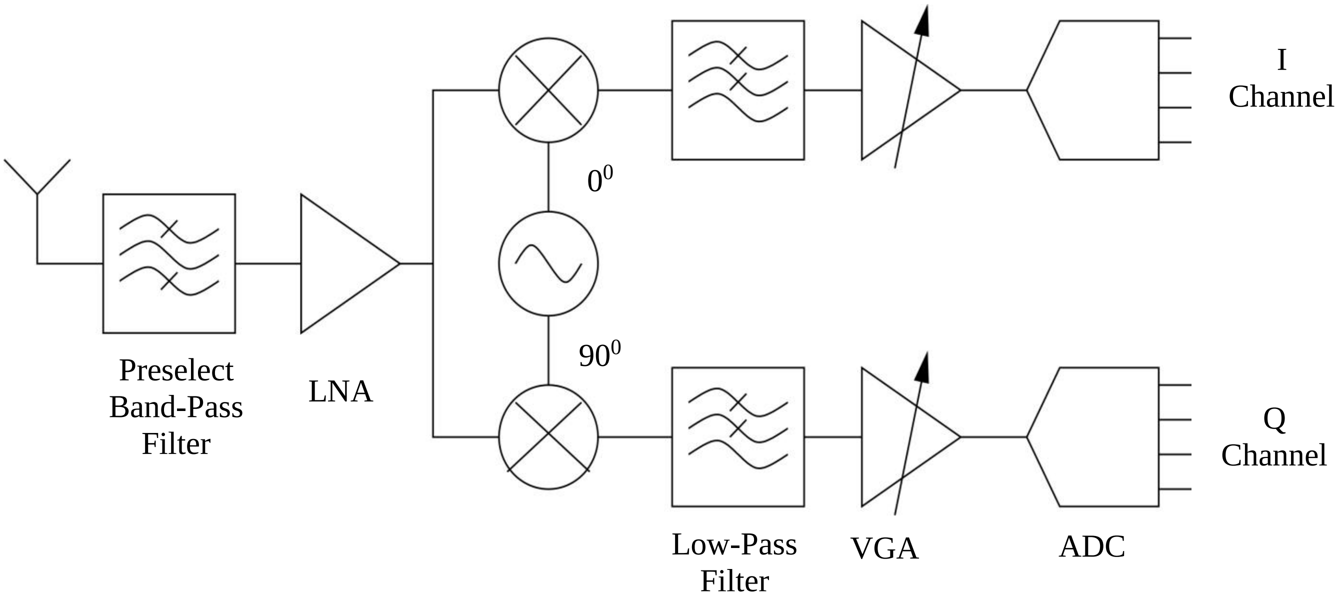


Figure 1: Analog front end of a typical MB-OFDM receiver as it exists

2.5. MB-OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation and multi access technique, and it has been studied over 20 years (Prasad, 2000). OFDM provides an efficient solution to wideband modulation. The entire allocated bandwidth, B, is divided into N sub channels. Data is transmitted on these sub channels in parallel using a 2- Dimensional M-ary modulation format. The figure 2 displays the spectral content of an OFDM system using M-ary Phase Shift Keying (MPSK).

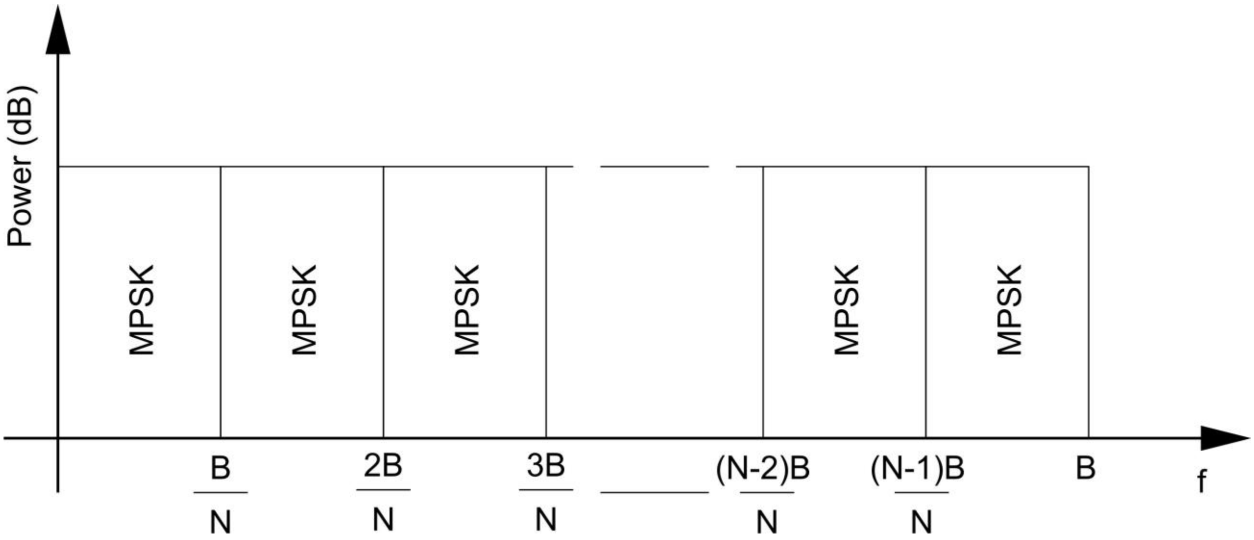


Figure 2: OFDM using MPSK on N parallel sub-channels

OFDM is spectrally encoded, and then converted to the time domain with inverse Fast Fourier Transform (iFFT) processor. Decoding is then performed with Fast Fourier Transform (FFT) processor.

MB-OFDM is a method of extending OFDM to larger bandwidths. The basic idea is dividing the bandwidth into sub-bands of 528MHz bands. Information is then transmitted using OFDM modulation on each band as shown in figure 3. Only one sub-band is activated at any given time. Every flow is then mapped to the orthogonal frequencies using the inverse fast Fourier transform (IFFT) of 128-points (Wu, 2012).

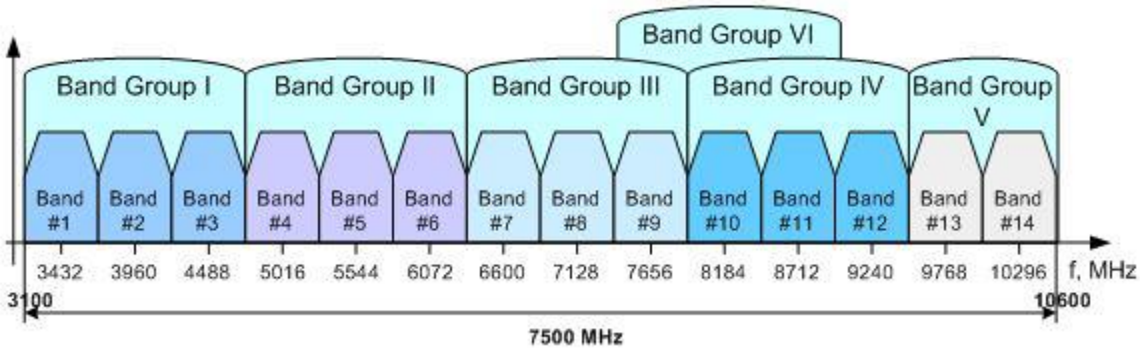


Figure 3: Spectral Division of MB-OFDM (A. Batra, 2004)

The MB-OFDM proposal indicates that in the first phase, three sub-bands will be used with center frequencies 3432 MHz, 3960 MHz, and 4488 MHz (A. Batra, 2004). Each sub-band will be active for the symbol period of 312.5 ns, after which 9.5 ns guard interval will be allotted for the receiver to switch to the next sub-band, which then becomes active for the next symbol period. The entire MB-OFDM bandwidth is thus 1.584 GHz, but the instanteneous bandwidth is only 528 MHz. Since any one sub-band is only active for third symbol, the transmit power can then be three times larger while still satisfying the FCC regulations.

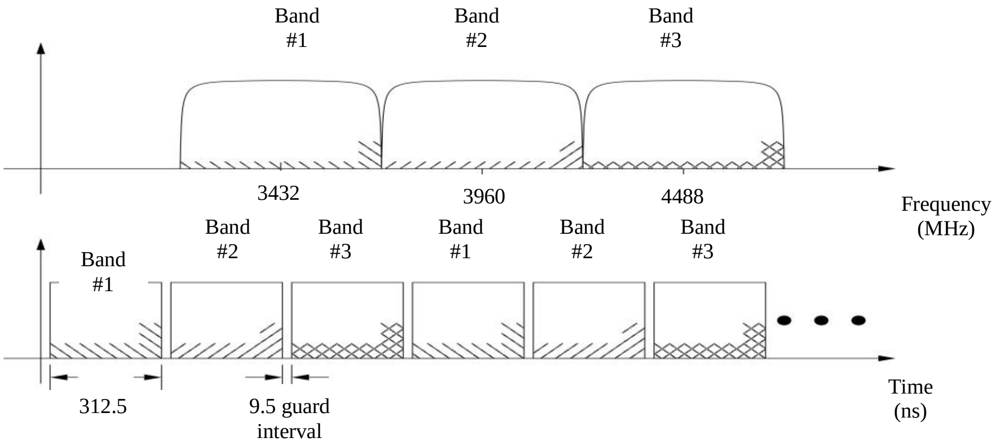


Figure 4: MB-OFDM for 802.15.3a sequentially modulates OFDM on different RF carrier frequencies

2.5.1. Effects of NBI on MB-OFDM

It is realized that the threat that NBI poses to UWB systems can be put into two. The first problem exists even for ideal receivers using floating point arithmetic and infinite full scale range and is a result of spectral leakage of the interference onto the MB-OFDM tones in the FFT output. The second problem is a result of non-idealities in the receiver. In order to prevent saturation of the ADC in large interference, the VGA gain is required to be set according to the interference power which may leave the information signal buried under the quantization noise of the ADC (Wu, 2012).

2.5.2. Interference reduction in UWB signals

A technique for reducing interference between a direct-sequence UWB communications system and a narrowband communications system uses interference-rejecting spreading codes to reduce signal power in a frequency band associated with the narrowband communications system. A method of operating an UWB communications system includes applying an interference-rejecting spreading code to a signal transmission. The interference-rejecting spreading codes is configured to reduce power in a particular frequency band of transmit or receive power spectral density associated with UWB signal without substantially reducing power outside that particular frequency band of transmit or receive power spectral density associated with the UWB signal. The methods that would be in this study can be classified as avoidance and cancellation techniques. Narrowband interference (NBI) avoidance methods are based on avoiding the transmission over the frequencies of strong narrowband interferers. The cancellation methods on the other hand aim at eliminating the effect of narrowband interference on the received UWB signal.

In dealing with NBI in UWB systems, it will be considered that there are some potential interferers with predetermined center frequencies and bandwidths. These interferers are the narrowband systems operating in the frequency band of 3.1 GHz to 10.6 GHz, and the most effective one among them is the IEEE 802.11a as in figure 5.

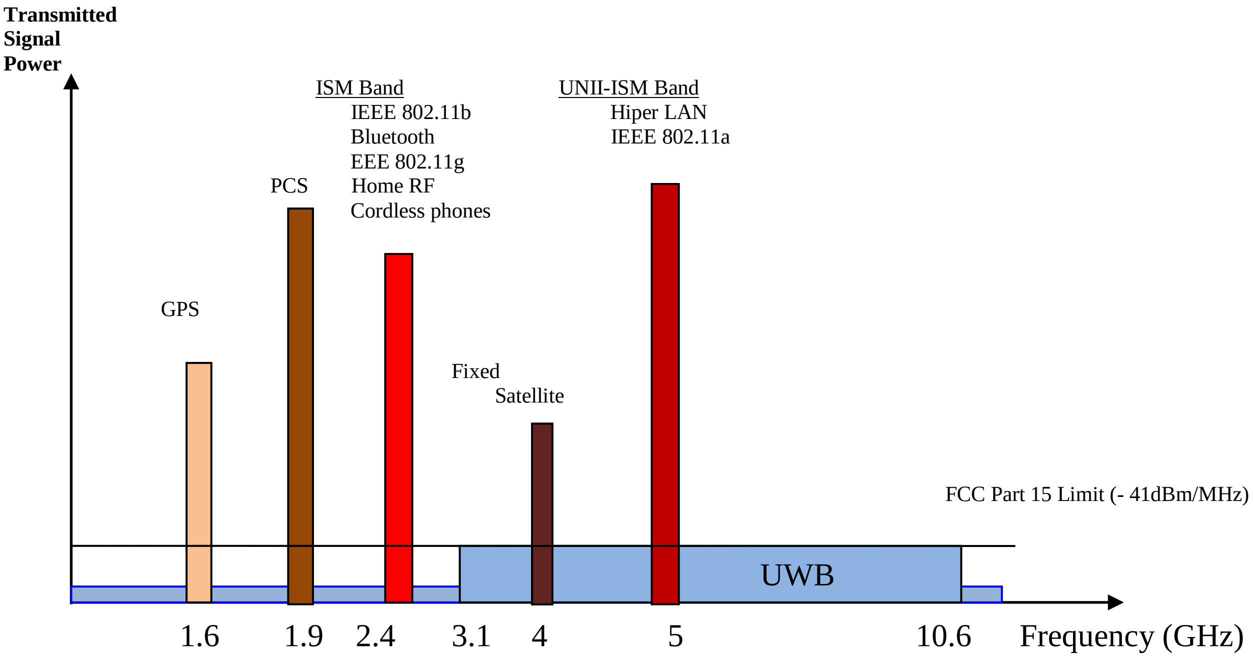
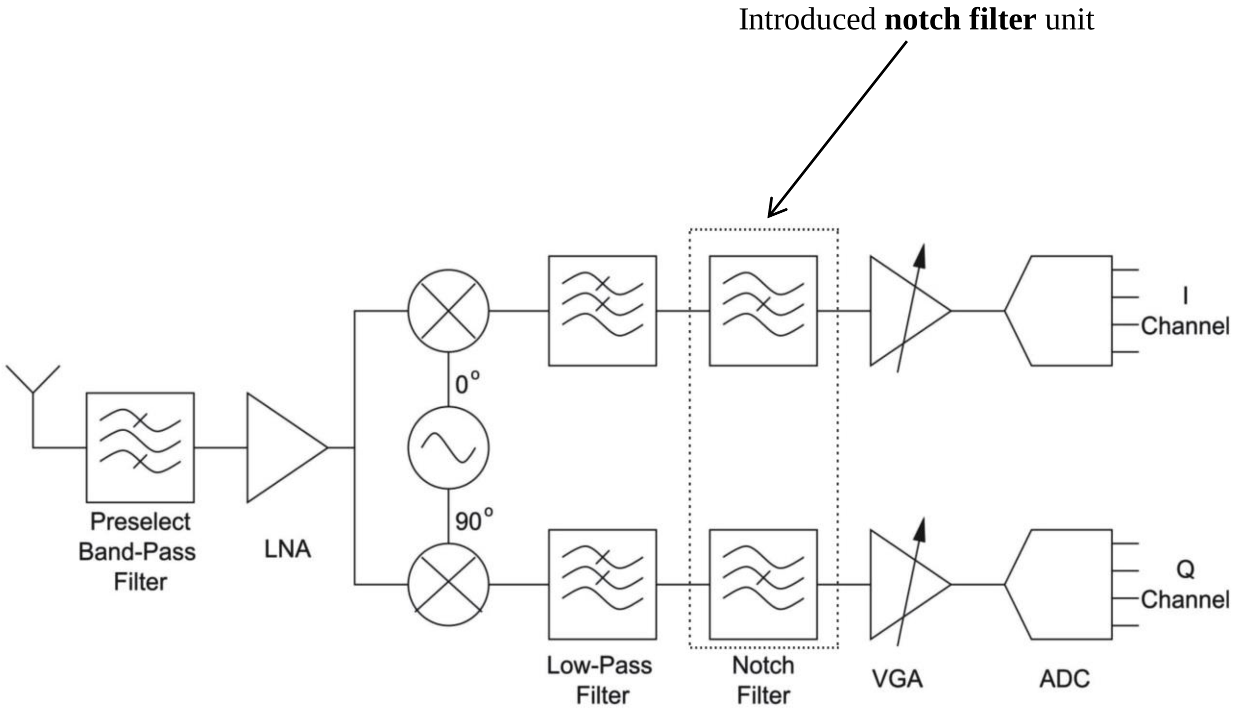


Figure 5: Spectrum crossover of the narrowband interferers in UWB systems (C. Carlemalm, 1994)

This IEEE 802.11a uses the 5GHz frequency band, which allows speeds up to 54Mb/s. Although in real-world, 802.11a hardware seldom, if ever, reaches that speed.

2.5.3. The conceptual model



Introduced **notch filter** unit

Figure 6: Modified UWB receiver analog front end with the inclusion of an analog notch filter

Notch filter is a band-stop filter with a narrow stop band (High Q factor). A band-stop filter or band rejection filter is a filter that passes most frequencies unaltered, but attenuates those in a specific range to very low levels (Techtarget, 2016). This unit is intended to suppress the 5GHz frequency band indicated in figure 5 with a maximum power level of between 20mW to 40mW compared to the UWB maximum power levels of 0.5mW.

2.5.4. Interference model

Investigation of the NBI models is a necessary initial step for identifying the interference which can be modeled in many ways depending on its type. One of the commonly used models considers NBI as a single tone, leading to;

$$i(t)=A\sqrt{2P_i}cos(2\pi f_ct+\phi_i), \qquad \text{Equation 1}$$

Where;

A = channel gain

P_i = average power

f_c = frequency of the sinusoid

ϕ_i = its phase

Another frequently employed model is based on the assumption that NBI is caused by a band limited interferer (L. Zhao and A. Haimovich, pp. 1684-1691 ,Dec. 2002).

The corresponding model is a zero-mean Gaussian random process and its power spectral density (PSD) can be shown as,

$$S_i(f) =\{^{Pint,}\ fc-B/2 \leq |f| \leq fc + B/2\} \qquad \text{Equation 2}$$

0, otherwise

Where,

B = bandwidth

f_c = center frequency of the interference

P_{int}= power spectral density within bandwidth

The received signal can be shown as,

$$x(t) = v(t) + i(t) + n(t) , \qquad \text{Equation 3}$$

Where,

$x(t)$ = received signal

$v(t)$ = UWB signal

$i(t)$ = NBI

$n(t)$ = additive white Gaussian noise (AWGN) with a PSD of N_0

The correlation between the samples of the received signal plays a significant role in the NBI identification analysis. This depends on the fact that the UWB signal has autocorrelation properties quite similar to that of AWGN, v(t) can be assumed to be part of n(t) for the sake of algorithm development. Along with this assumption, it has to be considered that n(t) is not correlated to i(t) and has an impulsive autocorrelation. Hence, if NBI is modeled as a single tone, the correlation between the samples of the received signal can be shown as (Murch, Sep 2004.),

$$R_i(\tau)=P_i|A|^2\cos(2\pi f_c\tau) + N_0\delta(\tau), \qquad \text{Equation 4}$$

Where,

τ = is the duration between the received samples.

In the case of the band limited interferer, the correlation function becomes,

$$R_i(\tau)=2P_iB\cos(2\pi f_c\tau)\mathrm{sinc}(B\tau) + N_0\delta(\tau) \qquad \text{Equation 5}$$

2.5.5. Power Levels of NBI at the Receiver

The MB-OFDM proposal provides some identification as to acceptable narrowband interference power levels. It does state that reliable communication can occur as along as the SIR is greater than -8 dB for a generic in-band tone interferer (A. Batra, 2004).

The minimum received power of the UWB data signal is P_{uwb} = -77.5 dBm, which is 6 dB above the sensitivity level for the 55 Mb/s data rate and is the measurement standard of the 802.15.3a working group (J. Ellis, 2002).This indicates that the maximum tolerable received interference power for this case is Print = -69.5 dBm.

Some electronic devices radiate within the UWB bandwidth and at power levels near the FCC limit. However, once the power of the interference reaches the UWB antenna will have attenuation due to path loss. The IEEE 802.15.3a channel modeling committee has provided a path loss model of:

$$P_L (f_g, d) = 20 \log_{10} (4\pi f_g d/c), \qquad \text{Equation 6}$$

Where P_L is the path loss in dB, d is the distance from the source in meters, $c \approx 3 \times 10^8$ m/s is the speed of light, and f_g is the geometrical average of the lower and upper corner frequencies (Foerster, 2002). In the case of the NBI, f_g can be approximated by the center frequency of the interference, $f_{int.}$ The smallest path loss occurs at the lower end of the UWB spectrum.

2.5.6. NBI Identification

For both NBI cancellation and avoidance techniques, determination of interference statistics is a highly required pre-process. In the proposed NBI approach, the main purpose is to obtain statistical information about the interference, which can facilitate NBI suppression. The most significant source of interference inside the UWB frequency band (3.1 to 10.6 Ghz) is the 802.11a WLAN systems as shown in the table 2 below (Anon., 1999).

Band (GHz)	Channel Number	Center Frequency (MHz)
U-NII lower band **(5.15 - 5.25)**	36	5180
	40	5200
	44	5200
	48	5240
U-NII middle band **(5.25 - 5.35)**	52	5260
	56	5280
	60	5300
	64	5320
U-NII upper band **(5.725 - 5.825)**	149	5745
	153	5765
	157	5785
	161	5805

Table 3: Frequency allocation for 802.11a WLAN

These systems have a bandwidth of 20 MHz and their center frequency lies in the 5.15 to 5.35 GHz or 5.725 GHz to 5.825 GHz band.

The three main factors characterizing the interference of the systems are;

- its model
- center frequency

- bandwidth

In each scenario, the main objective is to detect the existence of interference and if it exists, to find its statistics, most importantly the interference power.

2.5.6.1. Determined center frequency

The first case regarding NBI is the one in which the interferer is a single tone and f_c is already known. In order to find P_i, the correlation between the samples of the received signal is computed. When determining the correlation, attention should be paid that τ is not very close to 0, such that, according to (4), the AWGN related component has a negligible contribution to the correlation. Using the correlations computed for many different τ values, a decision about the existence of the NBI is automatically made and the received interference power is easily estimated (Haimovich, 2002).

A different situation occurs when the interference is band limited and f_c is given. In (5), which is the correlation function corresponding to this case, there is a *sinc*(Bτ) term. Considering that B has the fixed value of 20 MHz for 802.11a systems and does not exceed 50 MHz for any other narrowband interferer, and τ is in the nanosecond range, a reasonable assumption can be *sinc*(Bτ)$\underset{\sim}{}$1. With the help of this assumption and using the correlation of the received data samples, the system can be decided about the presence of NBI. P_{int} is determined perfectly for 802.11a systems, but with some proximity for interferers without explicitly known bandwidth.

2.5.6.2. Undetermined Center Frequency

Another possible scenario is being aware of the NBI model, that is, knowing whether it is a band limited or tone interferer, but having poor information about its center frequency. An 802.11a system, transmitting somewhere inside the lower and middle U-NII bands constitutes a proper example, since its bandwidth is known as 20 MHz but its center frequency can be anywhere in the 5.15 to 5.35 GHz band. Even without known f_c, it is possible to detect the existence of NBI in the UWB channel by measuring the correlation between the samples. P_{int}, however, can only be confined to a certain region ($fc - \Delta f/2 \leq f_c \leq f_c + \Delta f/2$), and the duration between the received samples (τ) is made as small as possible. These two requirements are to ensure that the value of the $f_c\tau$ product in the correlation functions (4) and (5) does not vary too much, so that the interference power can be estimated reliably (Haimovich, 2002).

2.5.6.3. Effect of Sampling Interval

For the case of unknown f_c, the accuracy of estimating P_{int} heavily depends on the sampling interval. Again, considering the 802.11a system described above, where the center frequency has an uncertainty of 200 MHz, for a reliable interference power estimation (in which the maximum error does not exceed 2%), τ has to be less than or equal to 0.1 ns. However, there are two basic drawbacks regarding such a small τ value. First, if the samples taken are so close to each other, noise is not uncorrelated anymore and the noise contribution in (5) cannot be ignore. Second, in order to have such a τ, the sampling rate should be even higher than chip-spaced, which is not feasible with the current technology. This problem can be overcome by exploiting the periodicity of the cosine term in (5).

Considering,

$$\cos(2\pi(fc \pm \Delta f/2)\tau) = \cos(2\pi(f_c \pm \Delta f/2)(\tau + k/(fc \pm \Delta f/2))) \qquad \text{Equation 7}$$

Where,

k = any integer whose periodicity feature allows τ to be increased by any multiple of ,

$1/(f_c \pm \Delta f/2)$.

Hence, by selecting an adequately high value of k, a realizable sampling rate can be achieved and a reliable estimation for P_{int} can be made.

The NBI identification approach is not limited to detecting the existence of interference or finding the NBI power. It can also be employed to find the entire correlation function $R(\tau)$ by computing the correlation values for all τ. $R(\tau)$ is required by many of the NBI avoidance and cancellation methods (I. Bergel, May, 2002, pp. 303 -307), (Letaif, March 2003, pp.233-237), (Murch, Sep 2004.), (L. Zhao and A. Haimovich, pp. 1684-1691 ,Dec. 2002).

Chapter 3: METHODOLOGY

Methodology is a framework within which the data are placed so that their meaning may be seen more clearly (Gill, 1991).

This chapter describes the research method used in carrying out the study. It describes the tools used in the research to bring forth the research objective that will accomplish the desired result. In order to evaluate this project, the methodology is focused on Design Science Research.

3.1. Design Science Research Methodology

3.1.1. Introduction

Design science research focuses on the development and performance of (design) artifacts with the explicit intention of improving the functional performance of the artifact. It is an application most notable in the engineering and computer science disciplines though is not restricted to these and can be found in many disciplines and fields (Vaishnavi, 2008).

3.1.2. Design Science Research Process Model

To bring the design activity into focus at an intellectual level, it is important to make a clear distinction between "natural science" and "science of the artificial" (also Known as design science). A natural science is a body of knowledge about some class of things – objects or phenomenon, in the world (nature or society) that describes and explains how they behave and interact with each other. A science of the artificial (design science), on the other hand, is a body of knowledge about the design of artificial (man-made) objects and phenomena – artifacts – designed to meet certain goals (Simon, 1996).

In this section, a model of the general process followed by design science is described. This model is an adaptation of a computable design process model developed by Takeda, et al. (1990). Different phases in design process are considerably different. Also, what makes the design science research process model different from corresponding design process model is the fact that contribution of new (and true) knowledge needs to be key focus of design science research (Takeda, 1990).

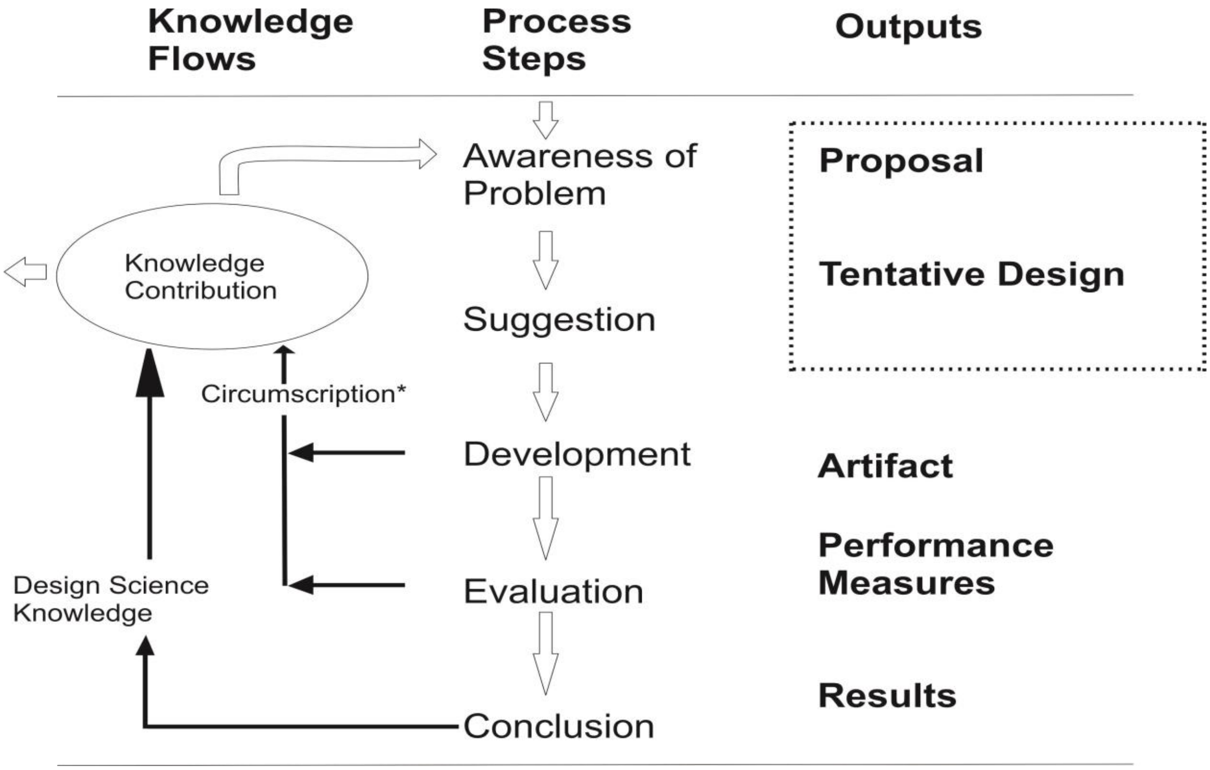


Figure 7: Design Science Research Process Model (DSR Cycle) (Takeda, 1990)

*Circumscription is discovery of constraint knowledge about theories gained through detection and analysis of contradictions when this do not work according to theory (McCarthy, 1980)

3.1.2.1. Awareness of the Problem

Awareness of an interesting research problem may come from multiple sources such as journals, text books, research papers gathered from libraries and the internet including new developments in industry or in a reference discipline. Reading in an allied discipline may also provide the opportunity for application of new findings to the researcher’s field. The output of this phase is a proposal, formal or informal, for new research effort (McCarthy, 1980).

In this particular study, a study of UWB was conducted realizing that UWB occupies a very wide frequency band, which forces it to coexist with numerous powerful licensed and unlicensed communication systems transmitting in the same band. The interference caused by these systems may complicate or even block the UWB communications. The most significant source of interference identified inside the UWB frequency band (3.1 to 10.6 Ghz) is the 802.11a WLAN systems as shown previously in the table 2 (Anon., 1999).

A need to combat these interferences in the UWB systems to realize its benefits was identified to be paramount.

Within the study period then, attention was on developing a model for narrowband interference control in UWB indoor wireless networks. Studies were conducted for UWB network systems using Multiband-Orthogonal Frequency Division Multiplexing (MB-OFDM) as in the figure 8 below.

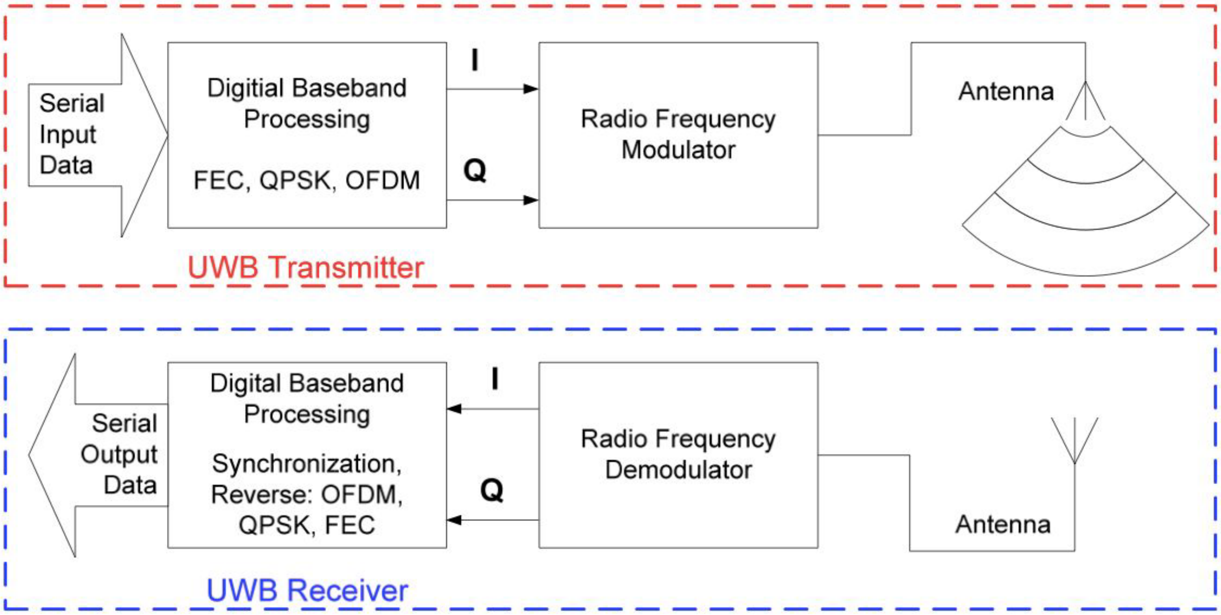


Figure 8: System Block Diagrams for MB-OFDM (Cook J.Gove N. Huggins B, 2007)

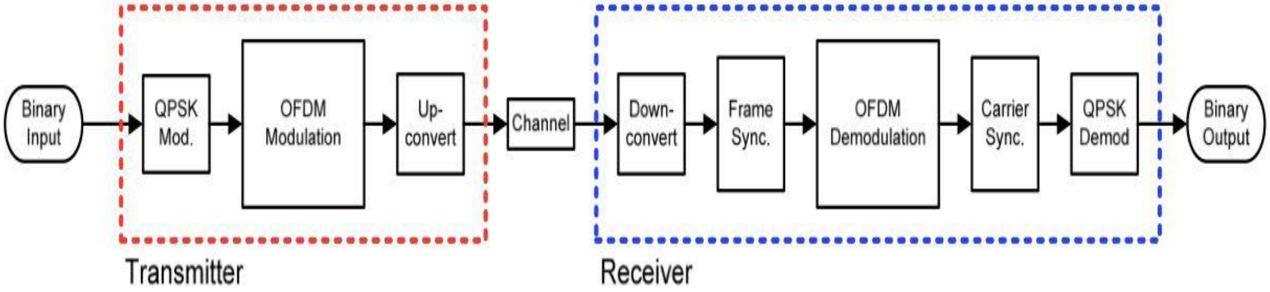


Figure 9 : System Block diagram for MB-OFDM (Cook J.Gove N. Huggins B, 2007)

3.1.2.2. Suggestion

The suggestion phase follows immediately behind the proposal and is intimately connected with it as the dotted line around Proposal and Tentative Design (the output of the suggestion phase) as indicated in figure 7. Suggestion is essentially a creative step wherein new functionality is envisioned based on a novel configuration of either existing or new and existing elements. The step has been criticized as introducing non-repeatability into the design science research method since human creativity is still poorly understood cognitive process. However the creative step has necessary analogues in all research methods; for example, in positivist research is inherent in the leap from curiosity about a phenomena to the development of appropriate constructs that operationalize the phenomena and an appropriate research design for their measurement.

In the research, upon the study, it was suggested to narrow down on the indoor UWB wireless networks. The diagrams in figure 8 and 9 are the transceiver concepts in UWB network making use of OFDM.

The project thus mainly focused on the receiver part of the whole UWB system since this is where the interference effects are realized. Figure 1 indicated an analogue front end of a typical receiver.

3.1.2.3. Development

The Tentative Design is further developed and implemented in this phase. The techniques for the implementation of course, will vary depending on the artifact to be created. An algorithm may require construction of a formal proof to show its correctness. An expert system embodying novel assumptions about human cognition in an area of interest will require software development, probably using a high-level package or tool.

The development phase was divided into hardware and software requirement.

3.1.2.3.1. Hardware requirement

The research is about coming up with a model for narrowband interference control for indoor UWB wireless networks.

While figure 10 shows the modified front end of the receiver to eliminate the NBI.

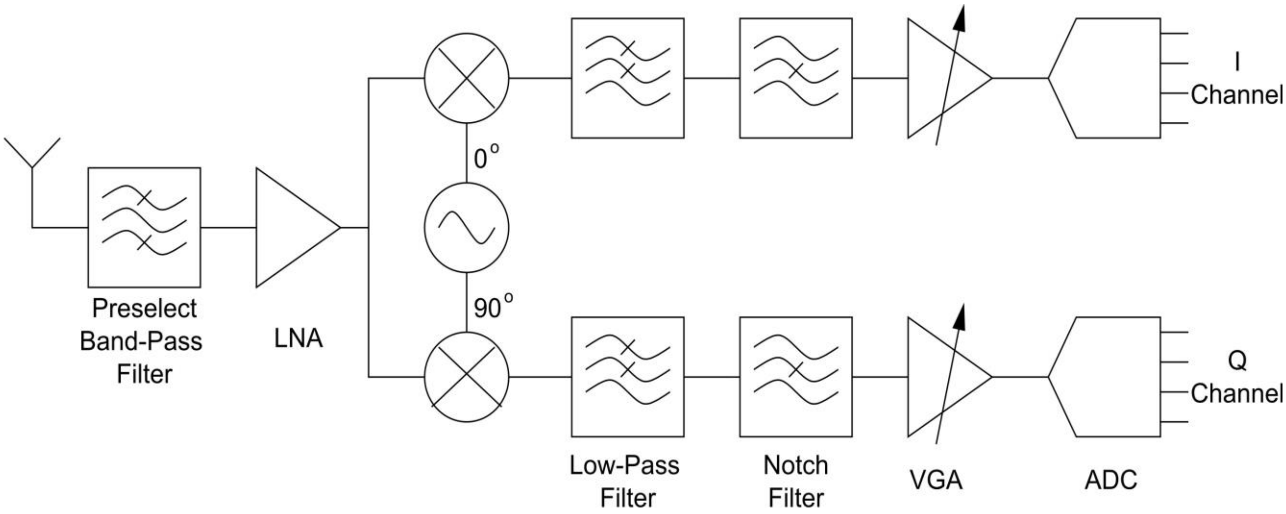


Figure 10: Modified UWB receiver analog front end with the inclusion of an analog notch filter

The system will have a bandwidth larger than 500 MHz or 20% of its center frequency and the power spectral density emission of below -41.3 dBm/MHz.

Below is the list of the electronic requirement and other materials that are to support this project.

- Band-Pass filter
- Low-noise Amplifier
- Mixer
- Low-Pass filter

- Notch filter
- Variable Gain Amplifier (VGA)
- Analog to Digital Converter (ADC)
- Antenna

3.1.2.3.2. Software requirement

Software requirement in this project is the need to applying software solutions to the designs generated to bring to realization the research question. It helps in transforming the designer's vision to reality before the actual physical implementation. This saves on the required cost of design and time in terms of the component requirement and time taken to put the components together.

CircuitMarker 2000 software has been chosen for this project. CircuitMarker is one of the most powerful, easy-to-use schematic capture and simulation tool with the capabilities to design electronic circuits and output netlists for TraxMarker and other PCB design tools and auto routers. It can also perform fast, accurate simulation of digital, analog and mixed analog/digital circuits using CircuitMaker's Berkeley Spice3f5/XSpice-based simulator (Ltd., 1988-2000).

Figure 11 shows the actual design of a Modified UWB receiver analog front end with the inclusion of an analog notch filter using CircuitMaker 2000.

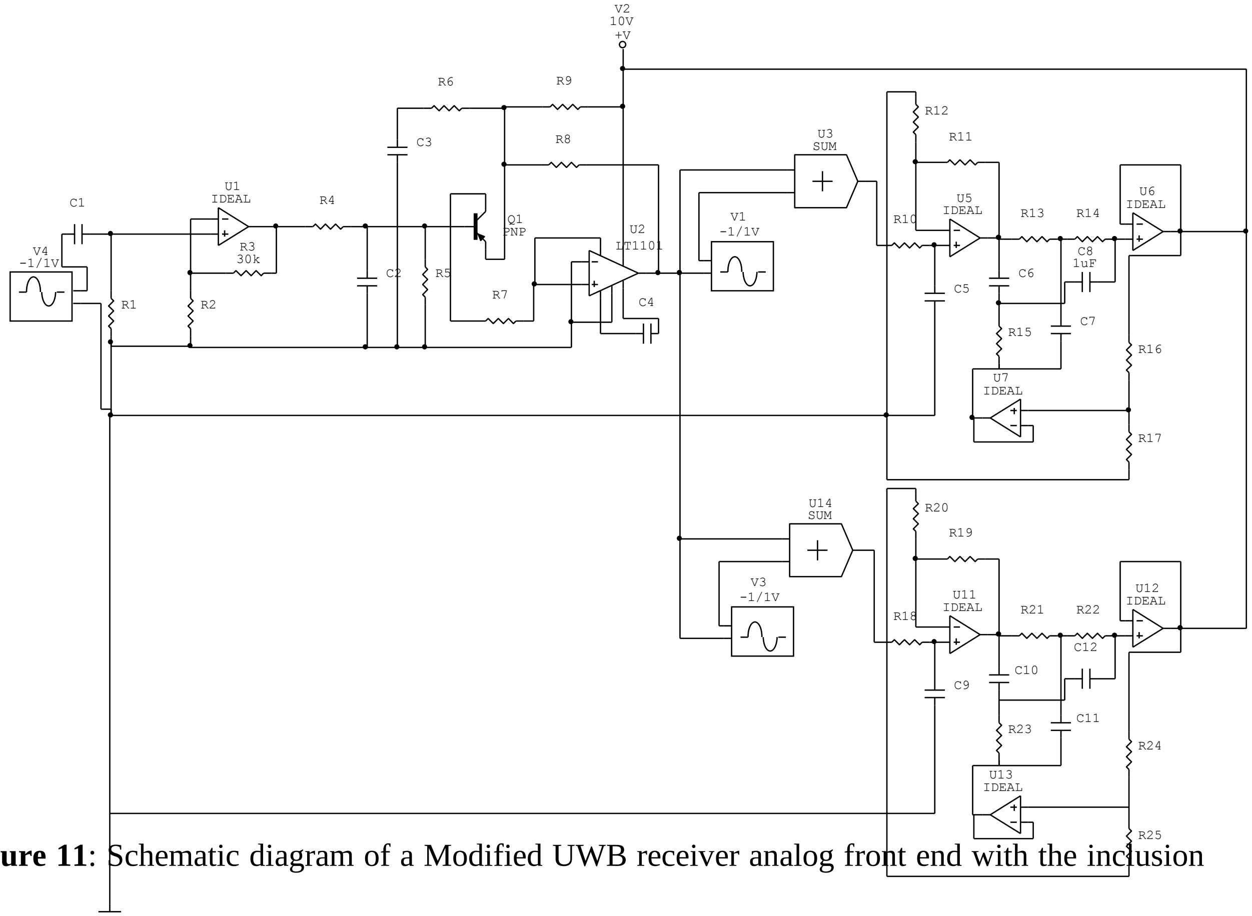


Figure 11: Schematic diagram of a Modified UWB receiver analog front end with the inclusion of an analog notch filter

3.1.2.4. Evaluation

Once constructed, the artifact is evaluated according to criteria that are always implicit and frequently made explicit in the proposal, (awareness of problem phase).

Once the circuit has been laid down using the CircuitMaker software, it will be simulated and tests done as per the expected results of the research.

3.1.2.4.1. Simulation

Network simulation is a technique where a program models the behavior of a network either by calculating the interaction between the different network entities using mathematical formulas, or actually capturing and playing back observations from a production network. The behavior of the network and the various applications and services it supports can then be observed through test equipment. Various attributes of the environment can also be modified in a controlled manner to assess how network would behave under different conditions (Asmussen, 2007).

The goal of using any simulator is to accurately model and predict the behavior of a real world system. Simulation methodology has become popular among telecommunication and computer network researchers and developers worldwide due to availability of sophisticated and powerful simulation packages, and also because of the flexibility in the model construction and the validation offered by simulation.

After using the CircuitMaker 2000 for designing the circuit in this project, simulation of the circuit follows using the same software. Several simulation characteristics that can be observed using this software are such as the output waveforms and also the characteristics of the project.

3.1.2.5. Conclusion

This phase forms the end of a research cycle or is the finale of a specific research effort. The finale of the research effort is typically the result of satisficing, that is, though there are still deviations in the behavior of the artifact from the multiple revised hypothetical predictions; the results are adjudged “good enough”. Not only are the results of the effort consolidated and “written up” at this phase, but the knowledge gained in the effort is frequently categorized as either “firm” – facts that have been learned and can be repeatedly applied or behavior that can be repeatedly invoked – or as “loose ends” – anomalous behavior that defies explanation and may well serve as the subject of further research (Gregor, 2013).

To achieve the required result supporting this research, it is important to realize the variance between the UWB circuit that has not been modified and the modified circuit to correct the NBI realized by this circuit.

Various test points are identified to help probe the circuit to find various desired results.

Considering a second order notch filter, after down conversion, interference could occupy any frequency within the continuous UWB baseband, which is 0-264 MHz. Most direct conversion receivers will have a high pass filter (HPF) to remove DC offsets after the mixer. The HPF will attenuate interferences that down convert to frequencies near DC. The problematic interferences thus have frequencies from a few MHz up to 264 MHz. The notch filter’s center frequency should accordingly be adjusted throughout this range, and a method should exist for adaptively changing the center frequency to match the interference frequency.

In a typical OFDM system, it would be desirable to set the notch filter’s bandwidth equal to that one of one OFDM sub channel, which in the case of the current proposal is 4.75 MHz (A. Batra, 2004).

In this phase, therefore it means that analysis of the artifact is done based on the performance of the circuit where the output requirement is performed well and successfully to identify and or realise the expected results.

3.2. Target population

A target population is the entire population, or group, objects or events that have particular characteristics of interest to a researcher for researching and analyzing.

As earlier indicated in chapter 2, that narrowband interference is not a resent problem, the following types of techniques were highlighted for mitigating narrowband interference (Letaif, 2003);

i. Processing gain technique
ii. Predictive technique (Letaif, 2003)
iii. Minimum Mean Square Error (MMSE) detectors technique
iv. Transform domain technique
v. Interference cancellation techniques including notch filtering

Some of the problems with these digital techniques come as a result of non-idealities in the analog front end of the filters. Which include amplitude clipping due to finite dynamic range and decreased Signal-to-Quantization-Noise Ratio (SQNR) as a result of finite precision of the Analog to Digital converter (ADC). Also it is important to note that in this carrier modulated wideband systems, the received signal, through the above process is down-converted to the baseband and sampled above Nyquist rate which allows it to be processed digitally. However, the UWB signal, being already in the baseband, cannot be sampled at the Nyquist rate with the existing technology. Therefore, the numerous narrowband interference suppression techniques proposed for other wideband systems, which can be realized by means of advanced signal processing methods, are not directly applicable to UWB systems (Sugiura, 2010).

To reduce these effects, interference needs to be reduced before the signal enters the digital domain. In (R. Pasand, 2004), a UWB receiver based on analog filter banks was proposed to suppress NBI. However, the analog power consumption and complexity of such a system are very high, since as many as 16 parallel filters and data converters were used in that work.

In this work, a single programmable analog notch filter is included in the base-band receive chain to reduce NBI before the signal is quantized. The filter is optimally placed after the baseband lowpass filter (LPF), and before the variable gain amplifier (VGA). Placing the notch filter after the LPF reduces its need to handle out of band interference, and placing it before the VGA reduces its linearity requirement.

3.3. Sampling and Sampling procedures

Sampling is a process used in statistical analysis in which a predetermined number of observations are taken from a large population. The methodology used to sample from a large population depends on the type of analysis being performed, but may include simple random sampling or systematic sampling.

According to Dr. Anthony Picciano in his book, A.G Picciano “Educational Research Primer”, he says that depending on the methodology being used in a study, sampling population may or may not be necessary. Studies that limit themselves to describing activity for specific population do not have to use sampling techniques but can accept whatever sample is available. This is frequently the case with historical, ethnographic, action and evaluation research.

In this research, upon the study of various technologies in the narrowband interference mitigations and their weaknesses as given by various researchers, and having studied the operation of a notch filter, it was arrived in inclusion of a notch filter in the receiver unit of the UWB technology setup.

The sampling technique thus used is a judgmental sampling in a non-probability sampling technique. A core characteristic of a non-probability sampling technique is that samples are selected based on the subjective judgement of the researcher, rather than random selection, which is the corner stone of probability sampling technique.

Chapter 4: CONCEPTUAL DESIGN AND IMPLEMENTATION

4.1. Design

As earlier indicated, the MB-OFDM proposal provides some indication as to acceptable narrowband interference power levels. It states that for a reliable communication to occur, the SIR must be greater than -8 dB for a generic in-band tone interferer (A. Batra, 2004). Moreover the received minimum power of the UWB data signal is P_{uwb} = -77.5 dBm, which is 6 dB above the resistive level for the 55 Mb/s data rate and is the measurement standard of the 802.15.3a working group (J. Ellis, 2002).

This indicates that the maximum tolerable received interference power for this case is;

$$P_{rint} = -77.5 \text{ dBm} + 8 \text{ dB}$$

$$P_{rint} = -69.5 \text{ dBm}$$

It is also important to take note that the bandwidth in consideration is UWB bandwidth of from 3.1 GHz to 10.6 GHz with a restricted maximum transmission power of -41.3dBm/MHz. Quite a very low power spectral density. Also that we are considering narrowband interferers operating within this UWB frequency and the most effective one being the UNII-ISM band operating within the frequency of 5GHz at high powers.

4.1.1. Filters Layout

4.1.1.1. Active Band Pass filter

This is a frequency selective filter circuit used to separate a signal at one particular frequency or a range of signals that lay within a certain band of frequencies from signals at all other frequencies.

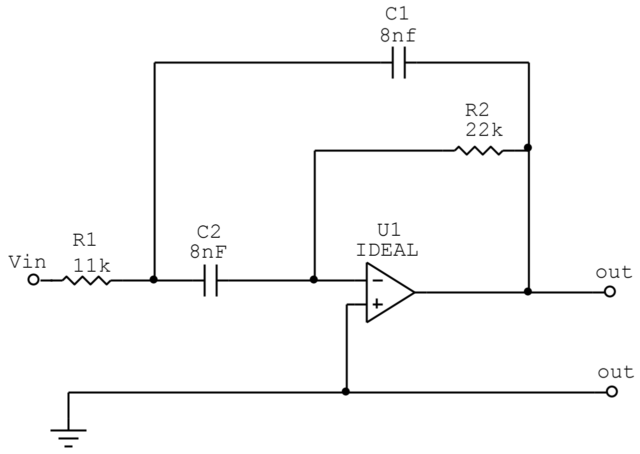


Figure 12: Infinite Gain Multiple Feedback Active filter

This type of active Band pass filter was selected to produce a “tuned” circuit based around a negative feedback active filter giving it high “Q-factor” (up to 25) amplitude response and steep roll-off on either side of its center frequency. Because the frequency response of the circuit is similar to a resonance circuit, this center frequency is referred to as the resonant frequency, (f_r).

Hence; $f_L = 3.1$ GHz

$f_H = 10.6$ GHz

Thus the filter bandwidth (BW) = $f_H - f_L$ Equation 8

$= 7.5$ GHz

Resonant frequency $(f_r) = \sqrt{f_L \times f_H}$ Equation 9

$=\sqrt{3.1 \times 10.6}$

$= 5.73$GHz

Quality factor of the BP filter $Q = fr / BW$ Equation 10

$=5.73/7.5 = 0.764$

Gain (Av) of the Operational amplifier = $-R_2/2R_1 = -2Q^2$ Equation 11

$Av = -2 \times 0.764^2 = 1.167$

But also, $f_r = 1/2\pi\sqrt{R_1R_2C_1C_2}$ Equation 12

$Q_{BP} = fr/BW_{(3dB)} = 1/2\sqrt{R2/R1}$ Equation 13

From equation 13 and equation 10, $0.764 = 1/2\sqrt{R2/R1}$

$(1.528)^2 = R2/R1 = 2.335$

The relationship gives R_2 being approximately twice R_1, thus we can choose any suitable value of resistances to give the required ratio of 2.335. Here we shall take R1 = 11kΩ and R2 = 22kΩ.

Assuming that C=C1=C2,

$C = 1/2\pi fr\sqrt{R1R2}$ Equation 14

$C = 1 / 2\pi(5.73\times10^6)\sqrt{11\times12} = 6.68nF \approx 8nF$

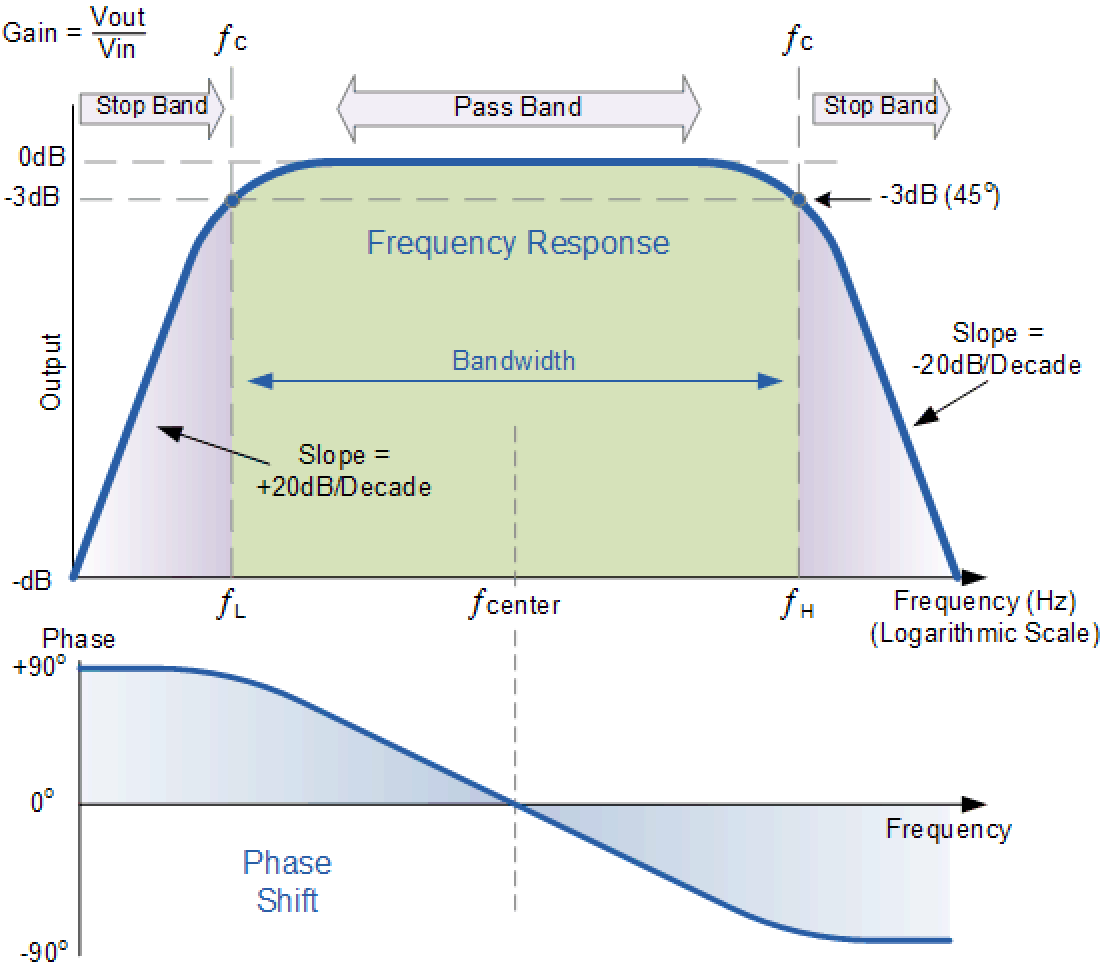


Figure 13: Active Band Pass Frequency response (Techtarget, 2016)

Figure 13 shows the normalized frequency response and phase shift for an active band pass filter.

4.1.1.2. Active Low noise Amplifier

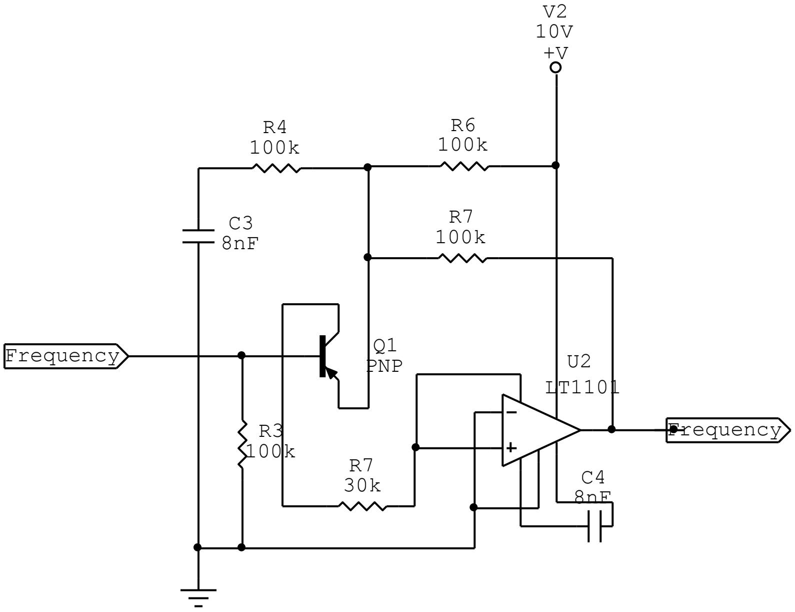


Figure 14: LNA

The low noise amplifier was arbitrarily carefully selected to match the intended results. It is used to amplify possibly weak signals within the selected range to acceptable required levels.

4.1.1.3. Signal Generator

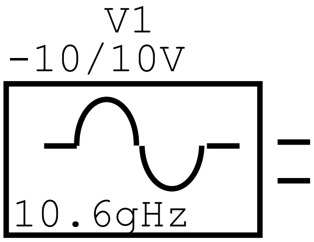


Figure 15: Signal generator

It would be important to maintain the frequencies allowed at the Band pass filter to retain the signals within the range.

4.1.1.4. Active Low Pass filter

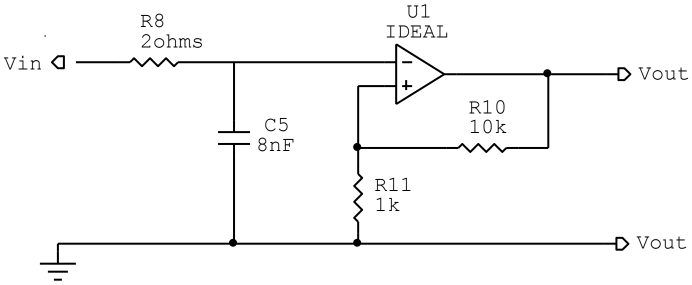


Figure 16: An active low pass filter

When the input signals are at low frequencies the signals will pass through the amplifying circuit directly, but if the input frequency is high the signals are passed through the capacitor C1. By this filter circuit, the output signal amplitude is increased by the pass band gain of the filter.

For a non-inverting amplifier circuit the magnitude of the voltage gain is obtained by its feedback resistor R_2 divided by its corresponding input resistor R_3.

Taking the amplifier gain of 10, the gain in dB is given as;

$$20\log(A_{max}) \qquad \text{Equation 15}$$

$$= 20\log(10) = 20\text{dB}$$

The voltage gain is given as $A_{max} = 10 = 1 + (R_2 / R_1)$ Equation 16

We shall take $\mathbf{R_1}$ to be 1kΩ, hence $\mathbf{R_2} = 9 \times 1\text{k} = 9\text{k}\Omega$ the nearest value being 9kΩ.

By considering the cut-off frequency equation;

$$f_c = 1/2\pi RC \qquad \text{Equation 17}$$

Take the cut off frequency to be 10.6GHz, and input impedance of 2Ω,

$$C = 1/(2\pi \times 2\times 10.6 \times 10^9) = 7.5\text{nF} \approx 8\text{nF}$$

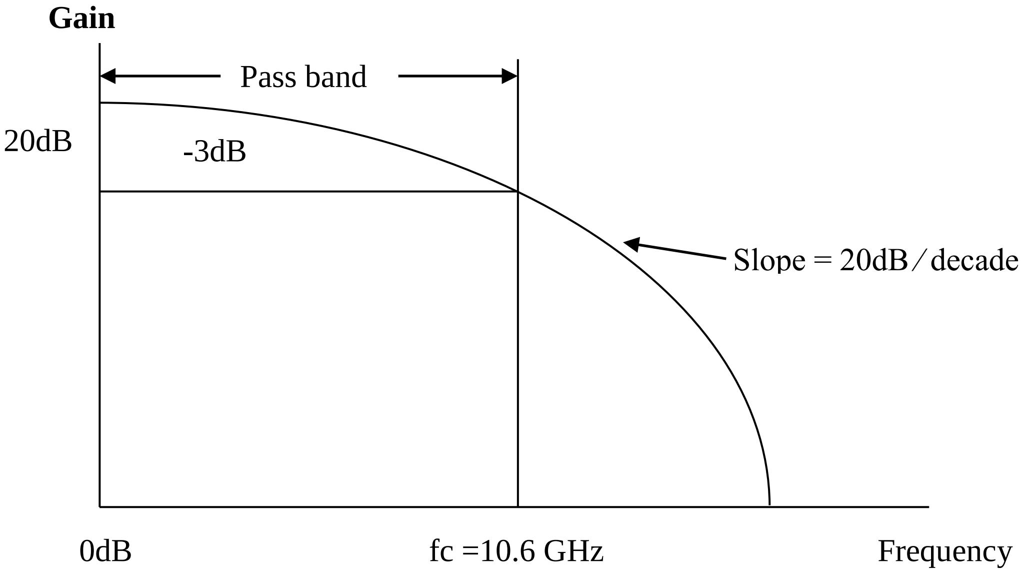


Figure 17: Frequency response of the active low pass filter

4.1.1.5. The Notch Filter

Notch filters are a highly selective, high-Q, form of band stop filter which can be used to reject a single or very small band of frequencies rather than the whole bandwidth of different frequencies.

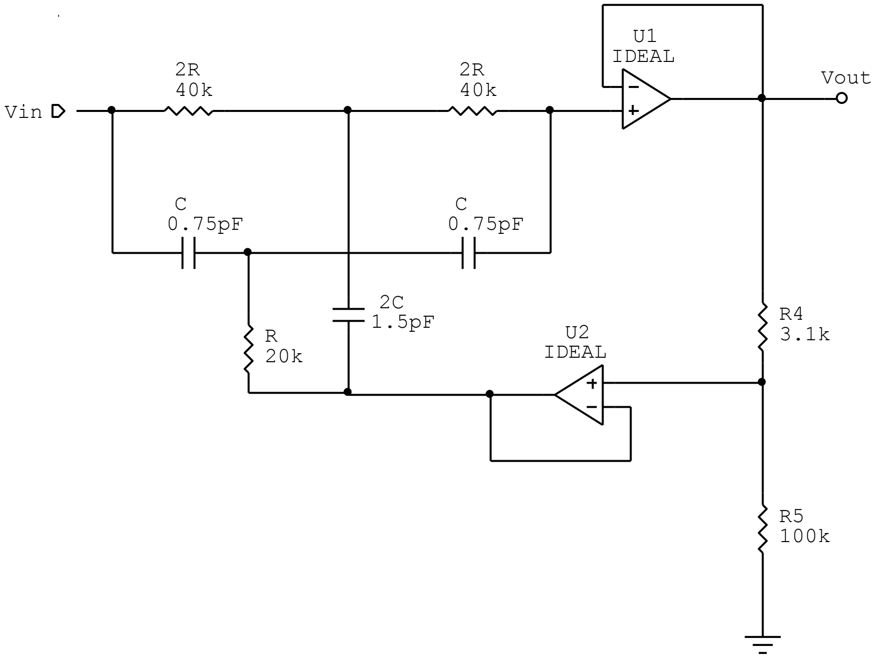


Figure 18: Notch filter design

$$R = 1/4\pi f_N C$$ Equation 18

Since our main source of interference here is the IEEE 802.11a at between 5.15GHz to 5.825GHz, this notch filter is designed to stop these frequencies from being processed.

We shall take a bandwidth between 5.15GHz to 5.825GHz.

The center frequency will be given by; $f_N = (f_L + f_H) / 2$ Equation 19

$= (5.15 + 5.825) / 2 = 5.4875\text{GHz}$

Hence we shall take our center notch frequency f_N to be 5.4875GHz and a -3dB bandwidth of 0.675GHz. Take the capacitance of 1nF.

As per the equation 19, $R = 1 / (4\pi \times 5.4875 \times 10^{6} \times 0.75 \times 10^{-12}) = 19.335\text{k}\Omega \approx 20\text{k}\Omega$

Quality factor $Q = f_N / BW$ Equation 20

Hence as per the equation 19, $Q = 5.4875\text{GHz} / 0.675\text{GHz} = 8.13$

Feedback value fraction $k = 1 - 1/4Q$ Equation 21

$K = 1 - (1/(4 \times 8.13)) = 0.97$

$k = 0.97 = R_5 / R_4 + R_5$ Equation 22

We shall take R_5 to be 100kΩ, then R_4 equals,

$R_4 = (R_5 - 0.97R_5) / 0.97 = 100\text{k}\Omega(0.031) = 3.1\text{k}\Omega$

The notch depth in dB = $1 / Q$ Equation 23

As per the equation 22, $f_N(\text{dB}) = 1 / 8.13 = 20\log(0.123) = -18.20$ dB

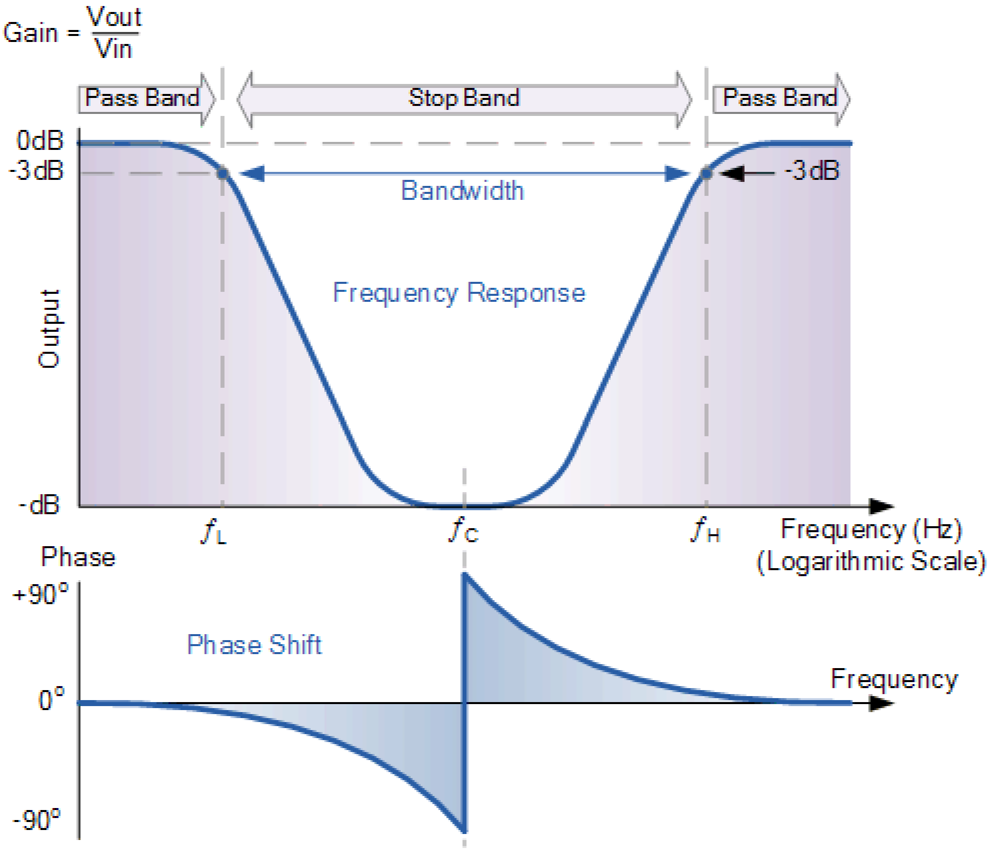


Figure 19: Notch filter frequency response (Techtarget, 2016)

4.2. Implementation

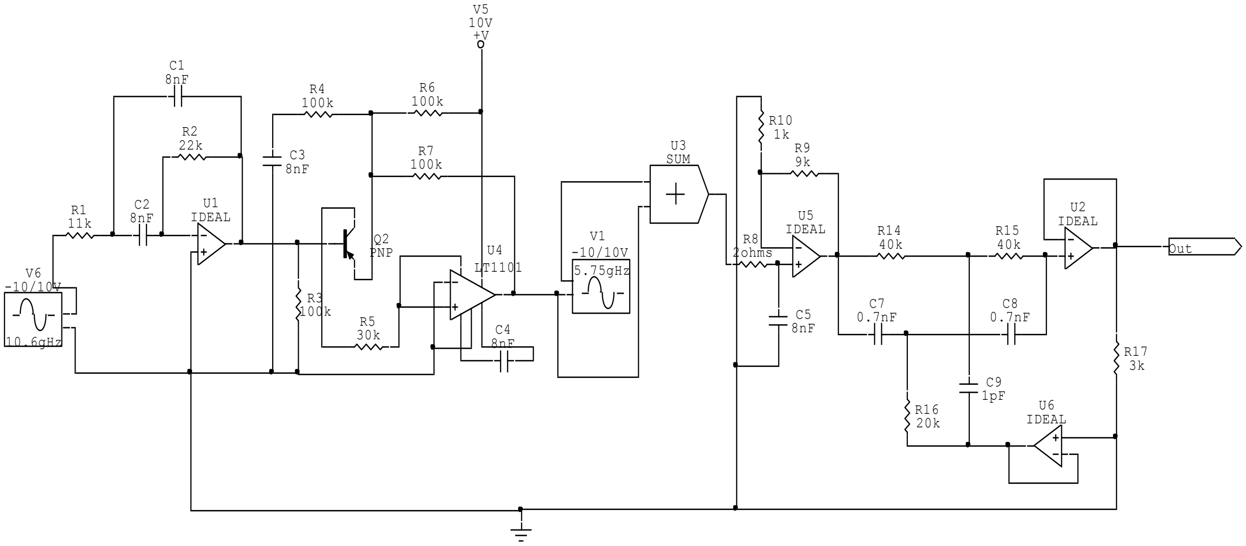


Figure 20: Assembled schematic diagram of UWB receiver with a notch filter

Chapter 5: TESTS, FINDING AND CONCLUSSION

5.1. TESTS

At this point various tests were conducted to ascertain the noise realized within the transmitted bandwidth of within 3.1GHz to 10.6GHz focusing on the IEEE 802.11a at between 5.15GHz to 5.825GHz.

A frequency of 10.6GHz with a biasing voltage of 10v was fed to the input of the Band pass filter and the output was tapped at point A of the filter as shown in the figure 21 of the schematic diagram and waveform figure 22.

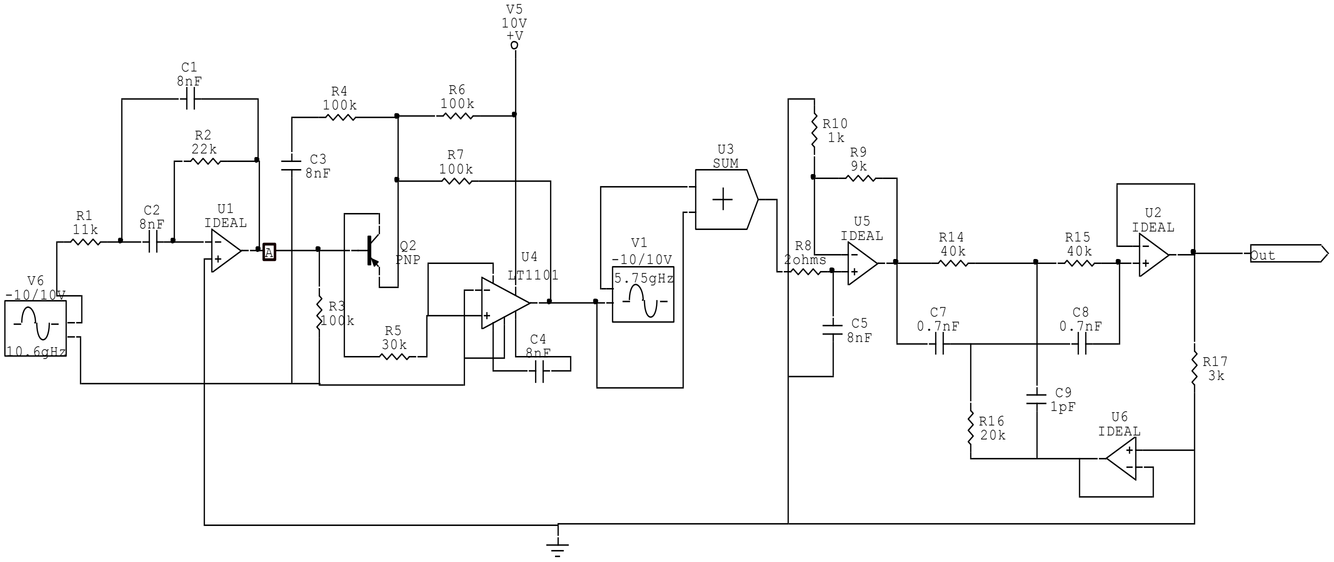


Figure 21: Schematic diagram with the output tapped at point A

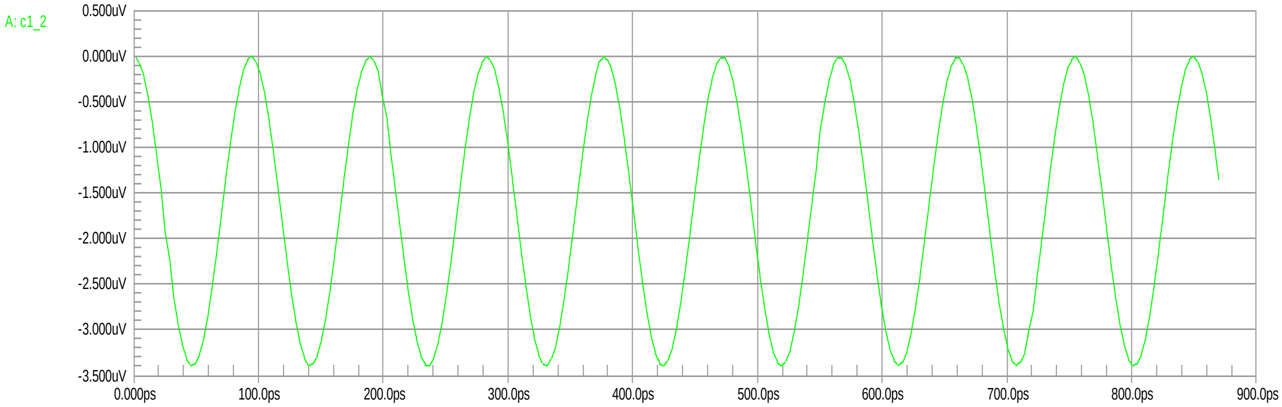


Figure 22: Waveform of the output tapped at point A

From the wave form;

$f = 1 / T$ Equation 24

$f = 1 / (140 \times 10^{-12}) = 7.14\text{GHz}$

$P_w = IV$ Equation 25

$P_w = -155 \times 10^{-12} \times -3.4 \times 10^{-6} = 0.000527\text{pw}$

Whose power is very small.

The signal was then fed to the Low Noise Amplifier and the result was as shown in figure 23 and 24 at point A of the LNA.

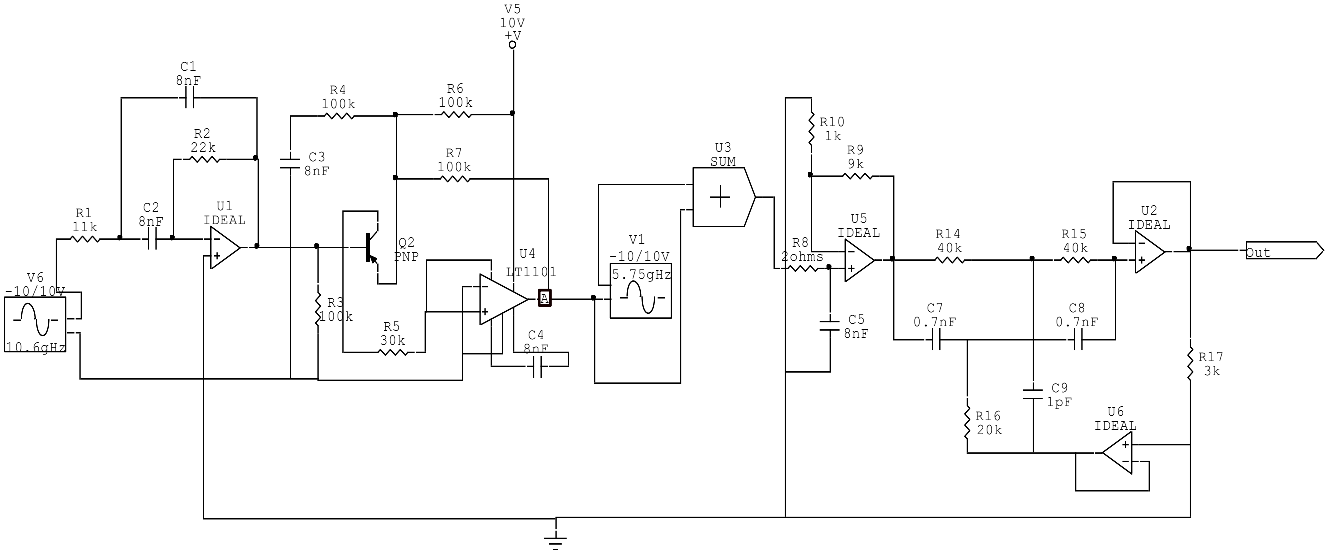


Figure 23: Schematic diagram with test point A of the LNA

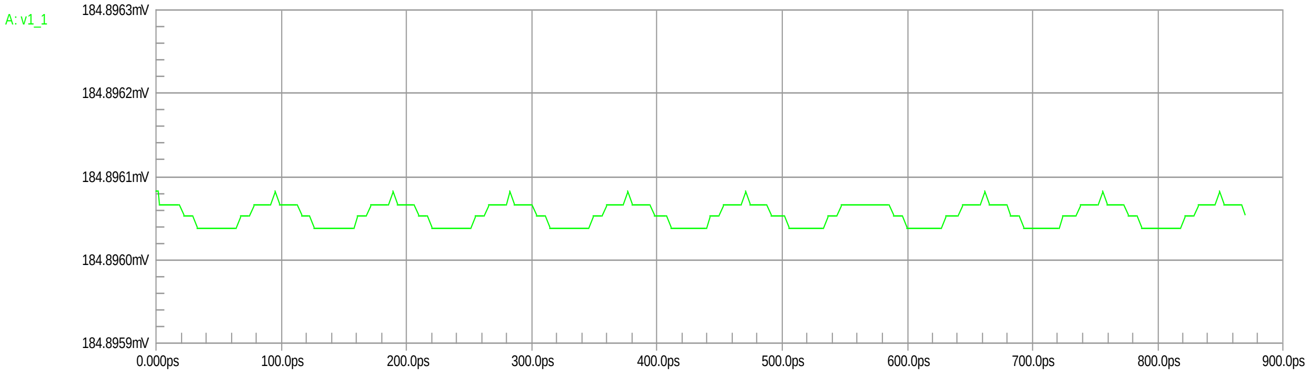


Figure 24: Waveforms at test point A of the LNA

It was realized that at this point the frequency and power were very low and interfered with greately. Hence the a need to bias and introduce a carrier to the signal as in figure 25 and 26.

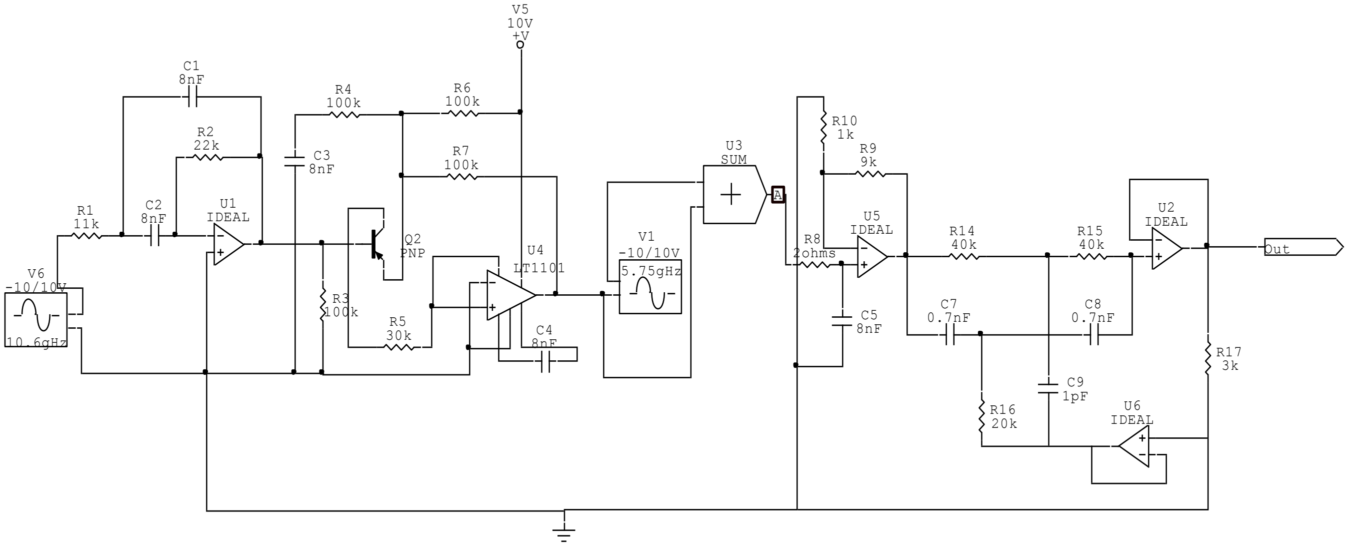


Figure 25: Schematic with an introduced carrier frequency with measured output at test point A

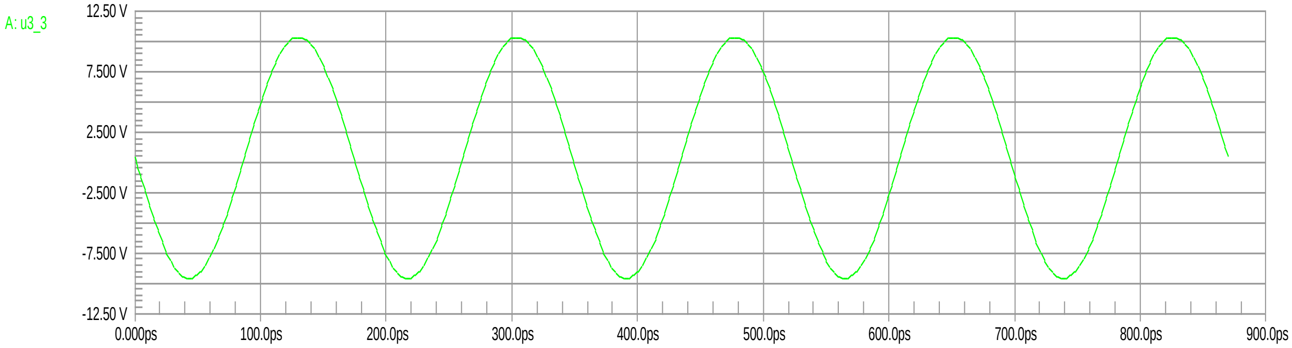


Figure 26: Waveform tapped at test point A of the summer

As per the equation 24,

$f = 1 / (165 \times 10^{-12}) = 6.06$ GHz

The signal was then fed to the Low Pass filter to only allow frequencies below 10.6GHz and the result at the LPF output test point A was as in figure 27 and 28.

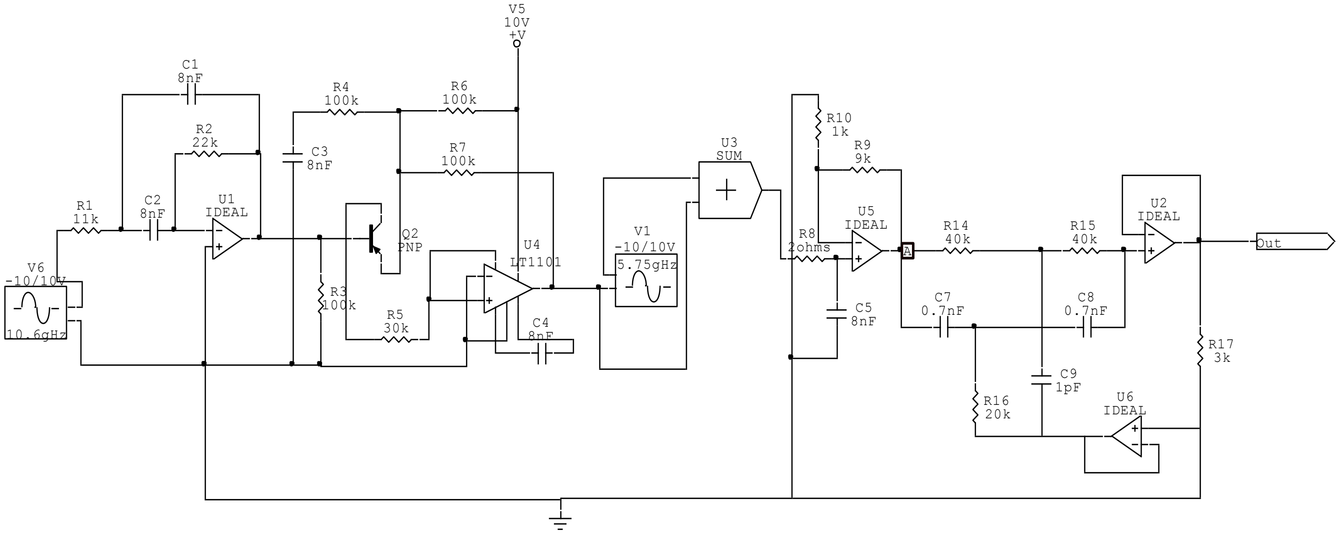


Figure 27: Schematic diagram output point A of the LPF

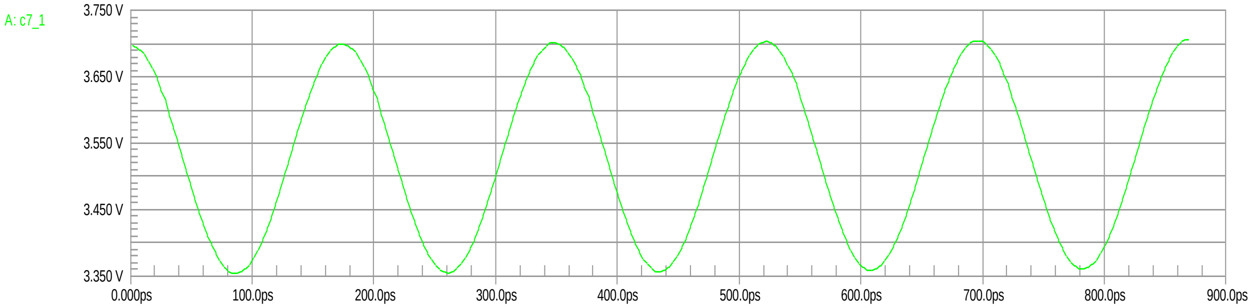


Figure 28: Waveform at test point A of the LPF

$f = 1 / (260 \times 10^{-12}) = 3.846$ GHz

Power $Pw = 34 \times 10^{-6} \times 0.35 = 0.0119$mW

The signal was then fed to the Notch Filter to eliminate the IEEE 802.11a frequencies and the results were as in figures 29 and 30.

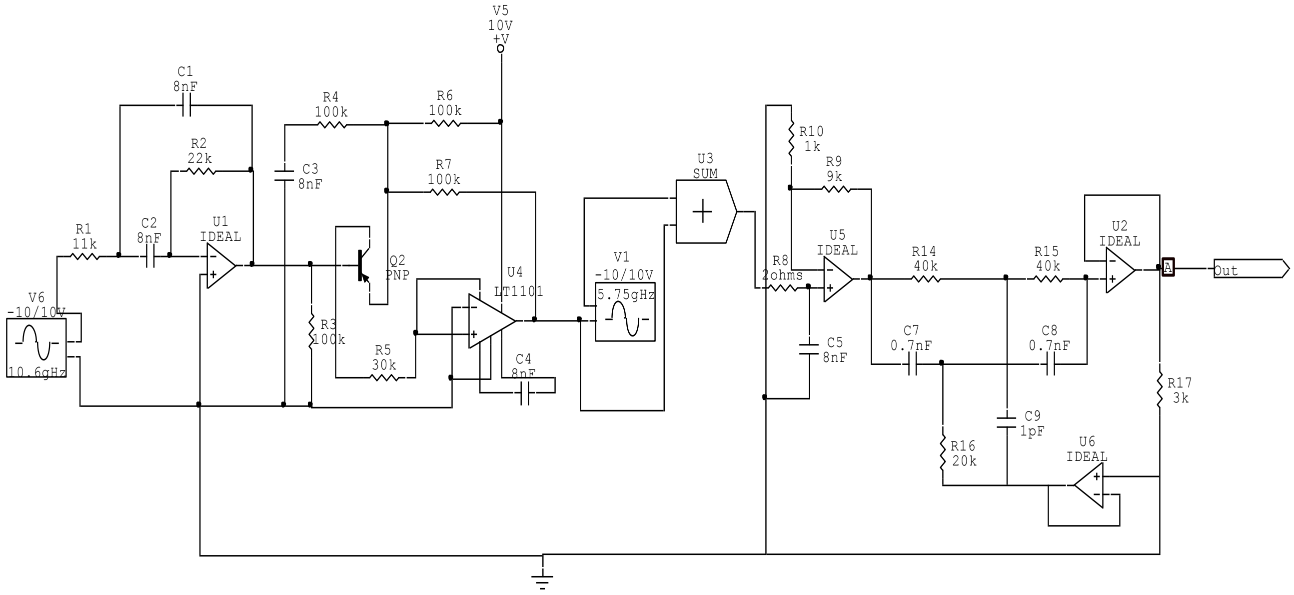


Figure 29: Schematic diagram of the Notch filter output at test point A

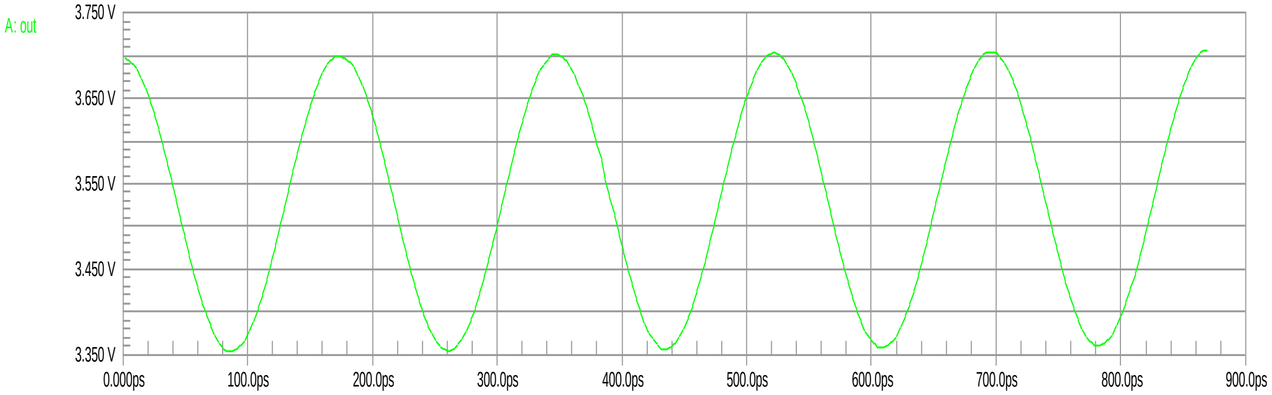


Figure 30: Waveform diagram at the notch filter output test point A

f = 1 / (260 × 10^{-12}) = 3.846 GHz

Power Pw = 0.12 × 10^{-3} × 0.35 = 0.0042mW

We realize that the frequency was retained within the range but the power dropped by 0.0077mW.

5.1.1. Summary of the attained results

Test point	**UWB Receiver without the notch filter frequency and power**	**UWB modified Receiver with the notch filter frequency and power**	**Comment**
Bandpass filter-A	7.4GHz/0.000527pw	7.4GHz /0.000527pw	Initial output stage
Low noise amplifier-A	6.25GHz/0.693µw	6.25GHz /0.693µw	Very Distorted signal
Mixer –A	6.05GHz/50.3w	6.05GHz /50.3w	Very high power
Low pass filter –A	3.846GHz/0.0119mw/ -19.244dBm	3.846GHz /0.0119mw/ -19.244dBm	Notch filter not yet introduced
Low pass filter –A	5.4875GHz/0.0170mw/ -17.69dBm	5.4875GHz/0.0170mW/ -17.69dBm	Voltage biased by -10/+10V
Notch filter –A	Notch filter introduced	3.846GHz /0.0042mw/ -23.76dBm	Power dropped by 0.0077mw biasing voltage still at -10v/+10v. Frequency cut to 3.846GHz.
Acceptable maximum tolerable received interference power for communication to occur	**-69.5dBm**	**-69.5dBm**	**The powers were within the acceptable range for communication to occur**

Table 4: Test results

5.2. Spectrums in (dBm) at various input and the outputs of the filters

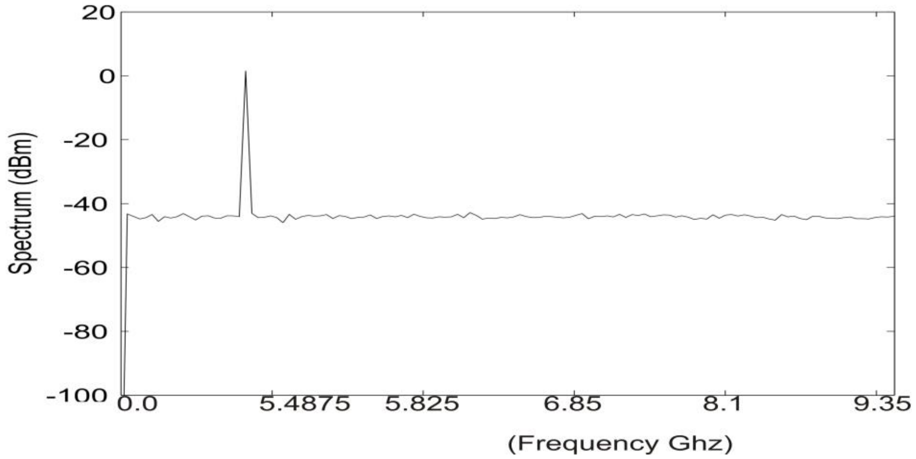


Figure 31: Spectrum input to the BPF for high power interference at SIR of -20dB figure 21.

Figure 31 show the UWB baseband spectrum when high power interferer at SIR = -20dB is present.

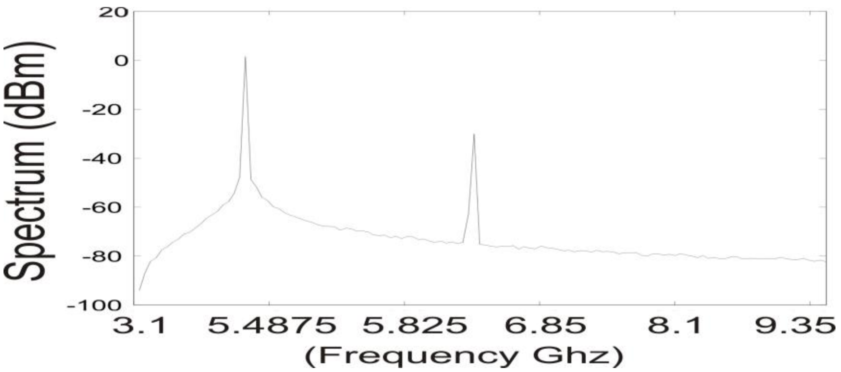


Figure 32: Spectrum at the BPF output at point A of figure 21

It is seen that from figure 32, the output contains interference as well as harmonics. The signal was then fed to the LNA and the spectral result was as in figure 33.

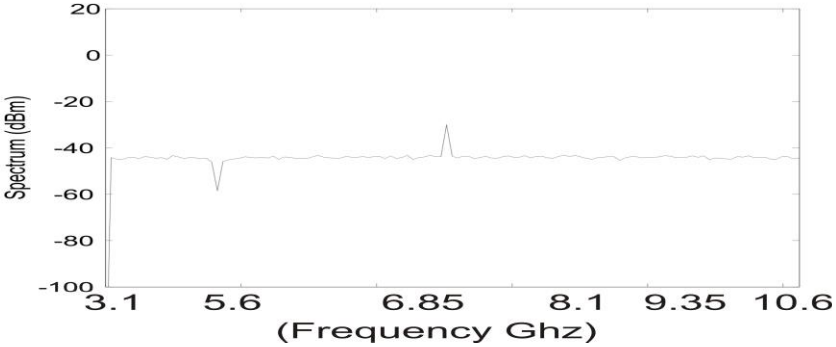


Figure 33: Spectrum result from the LNA output at point A of figure 23.

When a carrier was introduced to the low power signal using the 5.75GHz generator, the interference also was increased as shown in figure 33 below at the output of the LPF. The signal was fed to the Notch filter also referred to as a Band stop filter and the output realized at point A of figure 29.

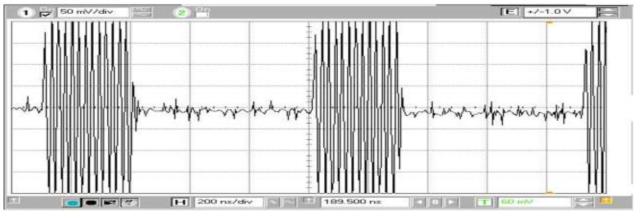


Figure 34: Periodic interference input applied to the notch filter at point A of figure 27.

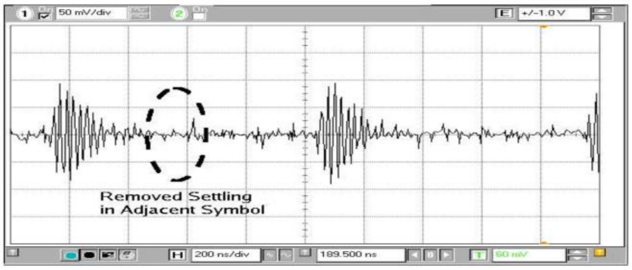


Figure 35: The settling behavior of the notch filter's output at point A of figure 29.

5.3. Findings

5.3.1. Objective one

It has been found that narrowband interferences may lie within the UWB bandwidth due to unintentional radiation of electronic devices as given in item 2.3.

Categorized as Out-of-Band and In-Band, OOB sources included microwave oven and existing communication standards such as WLAN, and Wi-Fi. These may not affect the UWB signals much because their frequencies are not within the UWB bandwidth, and also can be attenuated with RF surface acoustic wave and baseband low pass filtering without affecting the UWB data.

In-Band interferers range from computer components to common household devices such as electric shavers and hair dryers and similar ones under class-B compatible electronic devices. Such devices could legally have power levels of up to -41.3dBm/MHz, and those that are closer to a potential UWB receiver, such as computer components, possess a higher probability for degrading UWB receiver performance.

5.3.2. Objective two

While coming up with the model design, it was found necessary to put into consideration the MB-OFDM proposal for acceptable narrowband interference power levels for a reliable communication to occur, while suppressing or eliminating the powers and or frequencies of the UNII-ISM within the desired UWB band. It was realized that the maximum tolerable received interference power must be -69.5dBm that is the SIR must be greater than -8dB for a generic In-Band interferer.

5.3.3. Objective three

The received maximum interference power of -69.5dBm was not passed neither was the maximum transmission power of -41.3dBm/MHz. This shows the design was within the maximum thresholds required for communication with the elimination of the interferers.

The challenge realized was that the various powers realized at some point fluctuated too low that could impact communication in the actual design implementation. Also the notch filter eliminated most of the upper required frequencies within the UWB bandwidth remaining fixed to the MB-OFDM Band Group one.

5.4. Discussion of the results

The research shows that indeed UWB communication is offering different approach to the wireless communication compared to the conventional narrowband, promising very high data rates along with low cost hardware and low power consumption. The results can be useful to the various demands for wireless applications.

UWB communication as seen, is to be realized within a frequency range of 3.1GHz to 10.6GHz with an FCC broadcast power restriction of not in excess of -41.3dBm/MHz which is of a very low power spectral density hence being prone to interferences by other unlicensed frequencies within the same range transmitting at higher power levels.

In trying to mitigate and or eliminate such interferers, despite having been able to get powers and frequencies within the desired range, it was realized that at some point the original signal was almost being lost hence a need for regeneration which could impact on the cost of the equipment due to the regenerating systems.

The results realized were within the lower band group of the spectral division of MB-OFDM. This was attributed by the choice of the components that were limited only to and fixed to particular values. This means that for deployment of the model the way it is, then the frequencies to be realized would be within the band group one of the spectral division of MB-OFDM.

5.5. Conclusion

5.5.1. Objective one

With the exciting characteristics of the UWB technology, the limitations to transmission at low spectral density and coexistence with other licensed and unlicensed communication systems within the same frequency range but transmitting at higher power levels create concern for eminent interferences to enjoy the eminent attractive characteristics. Considering that the concern was for the indoor communication, the identified interferers considered were indoor interferers. All the signals considered as interferers emanate from equally important electronics within our domestic inclusions. Thus, a consideration must put in place to ensure that the operations of such equipment of need are not hampered with.

5.5.2. Objective two

It has been shown that the received interference power of many practical interference sources may pose a threat to reliable UWB communication. To manage this problem, a notch filter was introduced in the UWB receiver to eliminate the IEEE 802.11a signals which are between 5.15 to 5.825 GHz within the UWB bandwidth. In other earlier considered works with a notch filter was in a way that the UWB receiver based on analog filter banks but however, the analog power consumption of such arrangement and complexity of such system are very high hence a consideration of a single analog notch filter included in the base-band receive chain to realize the same.

5.5.3. Objective three

Implementation of this work came with its challenges where precision for the desired bands of frequencies instead of a single frequencies on a set of components was an uphill task. Component values had to be changed in turns to realize the various within band desired results since a single value variable component by its self could not be realized for the same.

5.6. Future work and suggestions

The extremely low powers realized were as a result of the choice of the components which impacted the design. Components values can be changed while tests are being conducted to realize a stable result. To successfully complete the design cycle, the interference detection and the center frequency tuning system need to be introduced, implemented and tested.

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