CHAPTER 2

UWB THEORY

2.1 INTRODUCTION

The transition from analog to digital cellular communication, the evolution of Third and Fourth Generation (3G and 4G) radio systems, and the replacement of wired connections with Wireless Fidelity (Wi-Fi) and Bluetooth are enabling the consumers to access a wide range of information from anywhere at any time (Ghavami et al 2006 and Han et al 2010). Every radio technology allocates a specific part of the spectrum; for example, the signals for Televisions (TVs), radios, cell phones, and so on are sent on different frequencies to avoid interference among themselves. As there are constraints on the availability of the RF spectrum, it is difficult to introduce newer radio services (Siwiak et al 2004).

To tackle the problem of increasing consumer demands and spectrum scarcity, UWB that allows the reuse of already occupied frequency bands is one of the solutions. Also, the FCC’s power restriction of -41.3 dBm/MHz for UWB allows the systems to reside below the noise floor of a typical narrowband receiver and this helps to accommodate new wireless communication services in the RF spectrum with minimal interference (Rahim 2006).
Filters are one of the essential components for UWB systems to suppress the interferences from the existing NB services when they coexist (Shi et al 2004, Shama et al 2006 and Siriwongpairat et al 2008). Therefore, considerable effort has been put in the research and development of UWB filters. Though a numerous of UWB filters are found in the literature using different structures and methods, those are relatively large in size, complex to design and their operational properties could be enhanced further. To overcome these drawbacks, this thesis starts with a conceptual view of UWB and filters, also expands on this idea to provide a practical solution for the application of filtering devices. This thesis mainly concentrates on the development of BPFs, BPFs with notch band(s), reconfigurable filter and design of digital filters.

2.2 ULTRA WIDEBAND

Ultra-wideband is a generic term to describe any radio system with large amount of bandwidth. In conventional NB communication systems, continuous carrier is modulated with a specific intelligence signal at transmitter and demodulation is carried out at the receiver. The inherent drawback of such systems is that a continuous wave signal has well defined signal energy in a narrow frequency band, which makes it very much vulnerable to being intercepted and messed with other services which are operating in the same frequency.

On the other hand, UWB systems employ short duration (nanoseconds to picoseconds) pulses with a very low duty cycle (< 0.5%) for the exchange of information. A duty cycle can be defined as the ratio of the on-time to total time. Equation (2.1) and Figure 2.1 gives the definition and pictorial representation of the duty cycle, respectively.
Figure 2.1 A low duty cycle pulse

![Figure 2.1](image)

(a)  (b)

Figure 2.2 UWB pulse in (a) time domain and (b) frequency domain

\[
\text{Duty cycle} = \frac{T_{on}}{T_{on} + T_{off}} \quad (2.1)
\]

Though the peak or instantaneous powers of individual UWB pulses are very high, they are transmitted only for a very short duration; the average power of such a signal becomes very low. The average transmission power in UWB system is in the order of microwatts, which is three order lesser than the transmission power of a mobile subscriber end user device. Consequently, UWB devices operated at very low transmission power leads to the longer battery life (Nikoor et al 2009). Owing to the inverse relationship between time and frequency, the shorter duration UWB pulses spread their energy across a very wide range of frequencies. Figure 2.2 illustrates UWB pulses in time and frequency domains.
This wide instantaneous bandwidth results from the time-scaling property of theoretical Fourier Transforms:

\[ x(at) \leftrightarrow \frac{1}{|a|} X \left( \frac{f}{a} \right) \]  \hspace{1cm} (2.2)

The notation on the left hand side of equation (2.2) shows a signal \( x(t) \) in time domain scaled by a factor ‘\( a \)’. The right side represents the same signal in the frequency domain, \( X(f) \), which is inversely scaled by the same factor ‘\( a \)’.

As defined by the FCC’s first report and order, UWB signals must have a bandwidth greater than or equal to 500 MHz or a FBW greater than or equal to 20% at all times of transmission. FBW is a factor used to classify signals as narrowband, wideband, or UWB and is defined by the ratio of bandwidth at -10 dB points to the center frequency. The following equation depicts this relationship.

\[ \text{FBW} = \frac{(f_H - f_L)}{(f_H + f_L)/2} \times 100\% = \frac{2(f_H - f_L)}{(f_H + f_L)} \times 100\% \]  \hspace{1cm} (2.3)

where, \( f_H \) and \( f_L \) are the upper and lower cut-off frequencies of a UWB spectrum. The classification of signals based on FBW is shown in Table 2.1.

**Table 2.1 Classification of signals based on fractional bandwidth**

<table>
<thead>
<tr>
<th>Signal</th>
<th>FBW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrowband</td>
<td>( \leq 1% )</td>
</tr>
<tr>
<td>Wideband</td>
<td>( 1% &lt; \text{FBW} &lt; 20% )</td>
</tr>
<tr>
<td>UWB</td>
<td>( \geq 20% )</td>
</tr>
</tbody>
</table>
2.3 ADVANTAGES OF UWB TECHNOLOGY

The inherent properties of short duration pulses used in UWB technology offer several advantages over narrowband communication systems as listed below:

- **Ability to share the RF spectrum:** The power level of the UWB signals is too low to be recognized by the existing radio services. However, this depends on the type of modulation used for data transfer in a UWB system (Multispectral solutions 2003). Some modulation schemes generate undesirable discrete spectral lines in their PSD, which can both increase the chance of interference to other systems and increase the vulnerability of the UWB system (to get interfered from other radio services).

- **Large channel capacity:** One of the major advantages of the UWB is large channel capacity which is defined as the maximum amount of data that can be transmitted per second over a communication channel. It is evident from Hartley-Shannon’s capacity formula:

\[
C = \log_2(1 + \text{SNR}) \text{ bits/s}
\]

where, C represents the channel capacity, B is the bandwidth, and SNR is the signal-to-noise ratio. As shown in Equation (2.4), channel capacity C linearly increases with bandwidth B and logarithmically decreases with the value of SNR (Shannon 1948). Therefore, UWB communication systems are capable of obtaining a data rate in the order of Gbps and possible of working in error prone communication channels with low SNRs.
• **Low probability of interception and detection:** Owing to the low transmission power, the probability of interception and detection is lower than the spread spectrum communication. In addition, UWB pulses are time modulated with codes unique to each transmitter/receiver pair (Battan 2003). Therefore, UWB systems hold significant promise of achieving highly secure, Low Probability of Intercept and Detection (LPI/D) communications that is a critical need for military operations (Nekoogar 2005).

• **Resistance to jamming:** Processing Gain (PG) is a measure of a radio systems’ resistance to jamming and is defined as the ratio of the RF bandwidth to the information bandwidth of a signal which is given in equation (2.5).

\[
PG = \frac{\text{RF Bandwidth}}{\text{Information Bandwidth}}
\]  

The frequency diversity caused by high PG makes UWB signals relatively resistant to intentional and unintentional jamming, because no jammer can jam every frequency in the UWB spectrum at once. Therefore, if some of the frequencies are jammed, there is still a large range of frequencies that remains untouched. However, this resistance to jamming is only in comparison to NB and wideband systems.
2.4 SPECIFICATIONS OF UWB

As per the text of FCC report and order, the following specifications are given to the UWB communication systems:

- **UWB bandwidth**: It is defined as the frequency band bound by the points that are -10 dB below the highest radiated emission based on the complete transmission system including the filter. The upper boundary is designated as ‘\( f_H \)’ and the lower boundary is designated as ‘\( f_L \)’.

- **FCC mask**: In order to protect existing radio services from UWB interference, the FCC has assigned conservative emission masks between 3.1 GHz and 10.6 GHz for commercial UWB devices. The maximum allowed PSD for these devices place them at the same level as unintentional radiators (FCC Part 15 class) such as TVs and Personal Computers (PCs). Based on the FCC regulations, UWB devices are classified into three major categories: communications, imaging, and vehicular radar. For communication devices, FCC has assigned different emission limits for indoor and outdoor UWB devices (Aiello et al 2006).

The spectral mask for outdoor devices is -10 dB lower than that of the indoor devices, between 1.61 GHz and 3.1 GHz, as shown in Figure 2.3. According to FCC regulations, indoor UWB devices must consist of handheld equipment and their activities should be restricted to peer-to-peer operations inside the buildings. The FCC’s rule dictates that no fixed infrastructure can be used for UWB communication in outdoor environments. Hence, outdoor UWB communication is restricted to handheld devices that can send information only to their associated receivers (Nikookar et al 2009). Table 2.2 and Figure 2.3 give the FCC radiation limits for the indoor and outdoor UWB communication systems.
### Table 2.2 FCC emission limits for indoor and outdoor UWB

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Indoor EIRP (dBm/MHz)</th>
<th>Outdoor EIRP (dBm/MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>960 MHz–1.61 GHz</td>
<td>–75.3</td>
<td>–75.3</td>
</tr>
<tr>
<td>1.61 GHz–1.99 GHz</td>
<td>–53.3</td>
<td>–63.3</td>
</tr>
<tr>
<td>1.99 GHz–3.1 GHz</td>
<td>–51.3</td>
<td>–61.3</td>
</tr>
<tr>
<td>3.1 GHz–10.6 GHz</td>
<td>–41.3</td>
<td>–41.3</td>
</tr>
<tr>
<td>Above 10.6 GHz</td>
<td>–51.3</td>
<td>–61.3</td>
</tr>
</tbody>
</table>

Figure 2.3 FCC emission mask for indoor and outdoor UWB communication systems
Table 2.3 Summary of UWB regulations in different countries

<table>
<thead>
<tr>
<th>Particulars</th>
<th>United States</th>
<th>Japan</th>
<th>Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency bands</td>
<td>3.1-10.6 GHz</td>
<td>Lower band: 3.4-4.8 GHz, Upper band: 7.25-10.25 GHz</td>
<td>Lower band: 3.1-4.8 GHz, Upper band: 7.2-10.2 GHz</td>
</tr>
<tr>
<td>Transmission power</td>
<td>-41.3 dBm/MHz</td>
<td>-41.3 dBm/MHz</td>
<td>-41.3 dBm/MHz</td>
</tr>
<tr>
<td>Operating bandwidth</td>
<td>FBW=20% or B=500 MHz</td>
<td>FBW=20% or B=450 MHz</td>
<td>FBW=20% or B=450 MHz</td>
</tr>
<tr>
<td>Operation limitation</td>
<td>Indoor and handheld systems</td>
<td>Indoor systems only</td>
<td>Indoor and outdoor systems</td>
</tr>
<tr>
<td>Interference mitigation technique</td>
<td>Optional</td>
<td>Mandatory at lower band by December 2008</td>
<td>Mandatory at lower band by June 2010</td>
</tr>
</tbody>
</table>
UWB has always been based on the principle of ‘underlay’ meaning that it must operate ‘under’ other services in the same spectrum without causing harmful interference to them. In the practical scenario, since it operates with a low transmission power, it may be suppressed by neighborhood and/or overlapping systems such as Global Positioning Systems (GPS) at 1.6 GHz, Personal Communication Systems (PCS) at 1.85 GHz, IEEE 802.11b/g and Bluetooth at 2.4 GHz, IEEE 802.11a at 5 GHz etc.

UWB may not cause harmful interference to the above mentioned services. The challenge is that the frequency bands and their respective applications are differing among countries. For example, US recently allocated spectrum in the 3.6 GHz band for WiMAX, and Europe allocated 3.4 GHz to 4.2 GHz. But, Japan has no WiMAX spectrum defined in 3.5 GHz band. One should consider these also before realizing devices like filters. UWB spectrum distribution is depicted in Figure 2.4 and Table 2.3 which show a summary of UWB regulations in those countries.

2.5 COMPARISON OF ULTRA WIDEBAND WITH EXISTING WIRELESS STANDARDS

Both Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS) techniques offer spreading of information in the frequency domain and provide advantages over NB communications such as lower PSD, covertness, frequency diversity for better performance in multipath channels, and resistance to intentional and unintentional jamming.

Although UWB and spread spectrum techniques share the same advantage of expanded bandwidth, the method of achieving the large bandwidth is the main distinction between the two technologies. In conventional spread spectrum techniques, the signals are continuous wave
sinusoids that are modulated with a fixed carrier frequency (Nikookar et al 2009), while in the UWB, signals are basically baseband and narrow UWB pulses are directly generate an extremely wide bandwidth (as we saw in Equation (2.2)), in the order of several GHz whereas Spread spectrum techniques can offer bandwidth in MHz.

Currently, a few active wireless IEEE standards, i.e., Bluetooth, IEEE 802.11a, IEEE 802.11b, and IEEE 802.11g, are commonly used in North America. In Europe and Japan, HiperLAN II is widely used, whose physical layer is similar to IEEE 802.11a. The Bluetooth radio employs FHSS with totally 79 hops. The frequency hopping range is from 2.402 GHz to 2.480 GHz. Its baseband modulation uses Gaussian Frequency Shift Keying (GFSK), where a binary one is carried out by a positive frequency deviation and a binary zero by a negative frequency deviation.

IEEE 802.11b employs DSSS with Complementary Code Keying (CCK) baseband modulation whose RF spectrum occupies 83.5 MHz bandwidth (for North America) which varies from 2.4 GHz to 2.4835 GHz. IEEE 802.11b has 11 channels, each of them 22 MHz wide and offers data speed up to 11 Mbps. Currently, it is the most widely used standard for PC wireless communication. IEEE 802.11a employs Orthogonal Frequency Division Multiplexing (OFDM) technology whose frequency spectrum occupies 300 MHz of total bandwidth at three different frequencies where each with a bandwidth of 100 MHz. The bandwidth at these three regions are Unlicensed National Information Infrastructure (UNII), lower band (5.15 GHz to 5.25 GHz), UNII middle band (5.15 GHz to 5.35 GHz), and UNII upper band (5.725 GHz to 5.825 GHz). It provides 12 channels of 20 MHz each and can offer data rate up to 54 Mbps.
IEEE 802.11g offers data speed up to 54 Mbps and operates on radio frequency between 2.4 GHz and 2.4835 GHz. It uses IEEE 802.11b's CCK to achieve bit transfer rate of 11 Mbps. In addition, IEEE 802.11g adopts IEEE 802.11a's OFDM modulation for data rate of 54 Mbps. IEEE 802.11g is compatible with IEEE 802.11b, but not compatible with IEEE 802.11a since IEEE 802.11g and IEEE 802.11a operate at different frequency bands.

IEEE 802.15.3a achieves up to 480 Mbps throughput with UWB technology. Now, there are two candidates suggested for UWB systems, namely, Multiband (MB)-OFDM and Direct Sequence Code Division Multiple Access (DS-CDMA). Among them, DS-CDMA has two frequency bands: one is from 3.1 GHz to 5.15 GHz, and the other is from 5.825 GHz to 10.6 GHz. M-ary Bi-Orthogonal Keying (MBOK) is employed in data bit modulation. On the other hand, MB-OFDM proposal divides the frequency range from 3.1 GHz to 10.6 GHz into totally 13 frequency bands of 528 MHz wide in each (Aiello et al 2006). There are 128 subcarriers inside each frequency bands with 4.125 MHz bandwidth. Among these 128 subcarriers, 6 of them are unused, 12 of them are pilot tones, 10 of them are guard tones and the rest 100 subcarriers are used to carry data. Both proposals can achieve 480 Mbps throughput, which is much faster than those of existing NB services as tabulated in Table 2.4.

In this area, various studies on UWB devices are under progress, especially in filters, which is one of the key passive components for UWB systems. This research focus on the development of filters for UWB systems.
### Table 2.4  Comparison of existing wireless communication standards and UWB technology

<table>
<thead>
<tr>
<th>IEEE Standards</th>
<th>WLAN</th>
<th>Bluetooth</th>
<th>WPAN</th>
<th>Zigbee</th>
<th>UWB</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11a</td>
<td>5 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>3.1 - 10.3 GHz</td>
</tr>
<tr>
<td>Operational frequency</td>
<td>54 Mbps</td>
<td>11 Mbps</td>
<td>54 Mbps</td>
<td>&lt;1 Mbps</td>
<td>55 Mbps</td>
</tr>
<tr>
<td>Maximum data rate</td>
<td>100 m</td>
<td>100 m</td>
<td>100 m</td>
<td>10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Maximum range</td>
<td>100 m</td>
<td>100 m</td>
<td>100 m</td>
<td>10 m</td>
<td>10 m</td>
</tr>
</tbody>
</table>

### 2.6 Characteristics of UWB Filters

The performance of the filter can be defined through the functional parameters like frequency bandwidth, insertion loss, return loss, group delay and phase (Stutzman and Thiele 1981). These are briefly discussed as follows:

**Frequency bandwidth**: Frequency bandwidth is the difference between upper and lower cut-off frequencies. It is an important design parameter that determines how well the filter performs over a frequency range. For NB systems, the bandwidth specified for a filter is very small because there is just one frequency that the filter is required to pass or stop. In the case of proposed work, every designed filter is able to cover the frequencies between 3.1 GHz and 10.6 GHz.

**Insertion loss**: It is a measure of loss of energy in transmission through a line or device compared to direct delivery of the energy without line or device. Let ‘P₁’ be the power received by the load when connected directly to the
source without line or device and ‘P₂’ is the power received by the load when the line or device is inserted between the source and load, while the input power is held constant, then

\[
\text{Insertion loss (dB)} = -10 \log \left( \frac{P_1}{P_2} \right)
\]  

(2.6)

The insertion loss may be contributed by (a) mismatch loss at the input, (b) attenuation loss through the device and (c) mismatch loss at the output.

**Return loss:** Return loss is another measure of impedance match quality, which is also dependent on the value of ‘Γ’ or ‘S₁₁’. Filter return loss is calculated by the following equation:

\[
\text{Return loss (dB)} = -10 \log |S_{11}| \text{ or } -20 \log (|Γ|)
\]  

(2.7)

**Group delay:** Group delay is the measure of relative delay at different frequencies from input to the output in a system. It is defined as the negative derivative (or slope) of phase response versus frequency. The group delay ‘τ’ of the filter is calculated from the phase of the computed transmission coefficient ‘S₂₁’ by using the following equation,

\[
τ = -\frac{dφ}{df}
\]  

(2.8)

where ‘φ’ is the phase of ‘S₂₁’ in radians/sec and ‘f’ is the frequency in GHz. This is an important characteristic because it helps to indicate how well a UWB pulse is transmitted and to what degree it may be distorted or dispersed.

**Phase:** Linear phase is a property of a filter, where the phase response is a linear function of frequency and, consequently group delay is constant at all of the frequencies.
2.7 DESIGN PROCEDURE OF UWB FILTERS

A filter is a two port network which is used to control the frequency response at a certain point in a microwave system by providing transmission at frequencies within the passband of the filter and attenuation in the stopband of the filter (Pozar 1998). The ideal filter would have a zero insertion loss in the passband, infinite attenuation in the stopband, and a linear phase response in the passband (Mattaei 1980).

There are two methods of designing filters, namely,

a. Image parameter method, and
b. Insertion loss method

a. **Image parameter method:** It consists of a cascade of simple two port filter sections to provide the desired cutoff frequencies and attenuation characteristics. But, it does not allow altering the specification of a frequency response over the complete operating range after the development. Although the procedure is relatively simple, to achieve the desired results through this method, more iterations are required on the design. Thus this method may yield usable response. But, there is no clear cut way to improve the design.

b. **Insertion loss method:** It uses network synthesis techniques to design filters with a completely known specified frequency response. This method allows a high degree of control over the passband and stopband amplitude and phase characteristics, with a systematic way to synthesis a desired response. Insertion loss results from the insertion of a device in a transmission line. There are tradeoffs between insertion loss, sharp cut-off and good phase response.
Filter design by the image method is conceptually the easiest filter design theory. There are two fundamental building blocks for image method filters, they are the constant-k and m-derived filter sections. The downfall of filter design by the image method is that the designs do not specify passband behavior of the filter. Filter design by the insertion loss method define both the passband and stopband performance of the filter. Hence, the Insertion loss method is chosen to design the filters in this thesis. The steps involved in filter design are illustrated in the Figure 2.5.

- **Filter specification**: Filter specification such as insertion loss, return loss, FBW, group delay and phase are chosen based on the type of filter to be designed and developed

- **Filter prototype design**: With the help of the software package (IE3D is used in this research) for the chosen specification and application, the filter prototype is to be designed
• **Scaling and conversion:** Scaling to the desired frequency and proper impedance match is done in this step

• **Fabrication and testing:** This is the final step of the filter development. After the fabrication of the filter, its functional parameters are characterized using a network analyzer

The proposed UWB filters with microstrip line technology uses Flame Retardant 4 (FR4) substrate, which is commonly used in Printed Circuit Board (PCB) to reduce the manufacturing complexities and cost.

2.8 **SUMMARY**

A detailed study on the basics of UWB technology has been presented. The inherent advantages and challenges in implementing the system have been addressed. The differences between conventional spread spectrum techniques and UWB are elucidated. The FCCs emission regulations for UWB systems have been discussed. Also, the characteristics and design procedure of realizing filter are presented in this chapter. Considering the procedures outlined in this chapter, the development of UWB BPFs and notch filters to suppress IEEE 802.11a/b, the prime interferer to UWB systems, are discussed in the following chapters.