MODELLING OF A TIME-MODULATED ULTRA-WIDEBAND COMMUNICATION LINK

AKAA ETENG and JUSTUS N. DIKE
Department of Electrical/Electronic Engineering
University of Port-Harcourt,
Port-Harcourt, Rivers State,
NIGERIA

ABSTRACT

The ultra-wideband communication technique involves the use of very large bandwidths and low spectral densities for information transmission. Time-modulated ultra-wideband (TM UWB) is an impulse-based ultra-wideband scheme that provides a direct means of increasing transmission bandwidth, thereby enabling data transmissions at high bit rates. This paper demonstrates the modelling of a single-user end-to-end TM UWB link in an Additive White Gaussian Noise (AWGN) channel. The developed model is validated by simulation in SIMULINK. The low bit-error rate characteristics of the link indicate that additive noise is not a significant channel impairment in a TM UWB communication link.

Keywords: Time-modulated, Ultra-wideband, modelling, simulation, Additive White Gaussian Noise, SIMULINK.

1 INTRODUCTION

Wireless communication has traditionally been achieved using narrowband communication schemes. However, in the strictest sense, no wireless communication is bandwidth-limited. Rather, beyond the spectral boundaries apportioned to a communication scheme, there is some amount of incident radiated power, making it necessary for communications regulatory agencies to define power limits for these out-of-band radiations [1].

The inherent narrowband nature of the established wireless communication technologies, such as Wi-Fi (IEEE 802.11) and Bluetooth, places a constraint on their achievable data capacity. However, the enormous bandwidth of ultra-wideband signals, should theoretically give ultra-wideband (UWB) technology an edge over these narrowband technologies. Furthermore, the low spectral power density of UWB signals should, in
principle, allow them to coexist with other existing wireless systems. These two major attractions have provided the motivation for the development of UWB-based Wireless Personal Area Networks (WPANs). In addition, there is interest in the research community toward the development of UWB-based Wireless Body Area Networks (WBANs) [2][3]. WBANs are body-centric wireless networks which can be used for patient monitoring, as well as other medical applications. The major attraction in this use of UWB is the low-power requirement of the technique, ultimately leading to low radiation levels for the human user.

UWB signals can be described as those signals with a fractional bandwidth greater than 0.20. Fractional bandwidth is defined by the following equation:

\[
B_f = \frac{B}{F_c} = 2 \frac{F_h - F_l}{F_h + F_l}
\]  

Where:
- \(B_f\) is the fractional bandwidth,
- \(B\) is the actual bandwidth,
- \(F_c\) represents the carrier frequency,
- \(F_h\) is the upper cut-off frequency,
- \(F_l\) is the lower cut-off frequency.

Alternatively, UWB signals can be defined as those with an ‘ultra-wide bandwidth’ greater than 500MHz. Ultra-wide bandwidth, in this case, is defined as, “the frequency band bounded by the points that are 10dB below the highest radiated emission”[4].

Shannon’s channel capacity theorem clearly shows the reasons for advocating an increased bandwidth [5]. By the theorem, channel capacity is given by:

\[
C = B \log\left(1 + \frac{S}{N}\right)
\]

Where:
- \(C\) is channel capacity,
- \(B\) represents signal bandwidth
- \(S\) stands for signal power,
- \(N\) represents the noise power.

This theorem reveals that narrowband systems have to strike a balance between increased channel capacities and transmit power. If the bandwidth is constrained, the required transmit power increases exponentially with increase in the channel capacity or data rate. However, channel capacity scales linearly with bandwidth. Consequently, UWB signals have the potential of achieving very high data rates with relatively low transmit power.

Broadly speaking, there are two classes of UWB radio systems, namely:

1. Multiband UWB, in which the UWB spectrum is split into sub-bands;
2. Impulse radio, in which the full UWB spectrum is utilized by generating very short duty-cycle pulses in the time-domain. Here, pulse duration \(\tau\) is typically in the order of one nanosecond or less.
Time-Modulated Ultra-Wideband (TM UWB) is an impulse radio scheme implemented using time-domain signal processing for the transmission and reception of information. The interval between two pulses is controlled by input information signals and a user-specific code sequence. The assigned code sequences eliminate possible collisions between multiple simultaneous users by assigning each user a unique time-shift pattern, thus preventing cross-channel interference. For a pulse width $\tau$, it has been shown that the optimum timing dither $\delta$ to be applied is $0.2304\tau$, to avoid intersymbol interference [6].

2 MODELLING

The modelling process is logically divided into three stages, namely:

1. signal generation
2. channel modeling
3. signal reception

The simulation software employed in the model validation is SIMULINK 7.0 running within MATLAB version 7.5 (R2007b).

2.1 Signal Generation

Although any pulse shape may be used for UWB communications, the pulse shape often used in the analysis of UWB systems is the Gaussian pulse. This preference is due to the mathematical tractability and ease of generation of this pulse shape [7]. Analytically, it is described by:

$$x(t) = Ae^{-\frac{(t-\mu)^2}{2\sigma^2}}$$

Where:

- $A$ is the pulse amplitude in volts,
- $t$ is the time in seconds,
- $\sigma$ is the standard deviation of the Gaussian pulse in seconds,
- $\mu$ is the mean value of the Gaussian pulse in seconds,
- $x(t)$ is the pulse at time $t$.

The duration of the Gaussian pulse $\tau$ in seconds is given by:

$$\tau = 2\pi\sigma$$

The typical Gaussian pulse has d.c. spectral components. Antennas, however, are unable to radiate d.c. components. Therefore, the use of the Gaussian pulse for information transmission will result in signal distortion at the transmitting and receiving antennas. Consequently, a higher-order derivative of the Gaussian pulse, which does not contain d.c. components is employed in this model. Higher-order derivatives can be recursively obtained from the relation:

$$x^{(n)}(t) = -\frac{n-1}{\sigma^2} x^{(n-2)}(t) - \frac{t}{\sigma^2} x^{(n-1)}$$

where $n$ is the order of the derivative [8].
The generation of time-modulated UWB pulses proceeds as follows:

1. A stream of fourth-order derivative Gaussian pulse are generated, defined as:
   \[ s^{(k)}(t) = \sum_j x(t) \] .................................(6)

   \( S^{(k)} \) is the \( k \)-th user's transmitted signal,
   \( x(t) \) is a single fourth-order derivative Gaussian pulse.

2. Each pulse is shifted to the beginning of a time frame:
   \[ s^{(k)}(t) = \sum_j x(t - jT_f) \] ................................. (7)

   \( T_f \) is the time-frame, or pulse repetition period,
   \( j \) is the index of the chosen time-frame.

3. Time-hopping is applied to the scheme to eliminate catastrophic collisions in a multiple access scenario:
   \[ s^{(k)}(t) = \sum_j x(t - jT_f - c_j^{(k)}T_c) \] ................................. (8)

   \( c_j^{(k)} \) is the time-hopping code – a pseudo-noise (PN) code,
   \( T_c \) is the duration of the time-chip within which the pulse is transmitted.

4. Data bits are used to pulse-position modulate this time-hopped UWB signal, resulting in the expression for time-modulated UWB:
   \[ s^{(k)}(t) = \sum_j w(t - jT_f - c_j^{(k)}T_c - \delta d_{(j/N_s)}) \] ................................. (9)

   \( d_{(j/N_s)} \) is the basic data sequence, representing information to be transmitted.
   \( \delta \) is the modulation index – the timing dither that applies to the UWB pulse when a binary ‘1’ is transmitted.
   \( N_s \) represents the number of pulses in a binary symbol.

2.2 Channel

The channel model is the Additive White Gaussian Noise (AWGN) channel, where a Gaussian distributed random noise process additively corrupts the transmitted signals. The signal at the receiver front-end, \( s_c(t) \), therefore, is a linear sum of transmitted signals, \( s(t) \) and the channel noise \( n(t) \). Concisely:

\[ s_c^{(k)}(t) = s^{(k)}(t) + n(t) \] ................................. (10)
2.2 Signal Reception

For the detection of the noise-corrupted signal, a correlator receiver is modelled. The following steps highlight the process:

1. The channel output $s_r(t)$ is correlated with a template signal $v(t)$ defined as:

$$ v(t) = w_{rec}(t) - w_{rec}(t - \delta) $$. 

(11)

$v(t)$ is a pulse shape defined as the difference between the expected fourth-order derivative Gaussian pulse and its delayed version, the time difference being $\delta$. To be effective, this template is first synchronized to the transmitter. Hence, it becomes:

$$ x_{temp} = v(t - jT_f - c_j^{(k)} T_c) $$. 

(12)

The received signal stream is correlated against this template sequence, and the result integrated over a bit period. The output of the integrator is given as:

$$ z = \int_{\tau_i + jT_f}^{\tau_i + (j+1)T_f} r(t) v(t - jT_f - c_j^{(k)} T_c) dt $$. 

(13)

$$ = \int_{\tau_i + jT_f}^{\tau_i + (j+1)T_f} [s(t) * h(t)] v(t - jT_f - c_j^{(k)} T_c) dt $$

$$ + \int_{\tau_i + jT_f}^{\tau_i + (j+1)T_f} n(t) v(t - jT_f - c_j^{(k)} T_c) dt $$

$$ = Y_{tm} + N_{tm} $$. 

(14)

$Y_{tm}$ is the required data sequence, while $N_{tm}$ is a noise term arising from AWGN present at the receiver input.

After the integration stage, a decision is made whether the result represents a ‘0’ bit or a ‘1’ bit. This decision is reached by comparing the energy of $s(t)$ over a bit period with a threshold value, in this case 0. Logically,

$$ s_r(t) = \begin{cases} 
0, & \int_{\tau_i}^{\tau_i} s'(t) < 0 \\
1, & \int_{\tau_i}^{\tau_i} s'(t) \geq 0 
\end{cases} $$

(15)

3 SIMULATION

Equations 3 to 9 are the basis of the simulation of a TM UWB generator shown in Figure 1. The simulation parameters are presented in Table 1.
The UWB pulse generator block accepts inputs from the ‘User 1 Data’, and Code Generator blocks, both of which are first concatenated to form a row matrix. The data bits are used to effect a pulse-position modulation on the fourth-order derivative Gaussian pulses generated in this block. The code sequence is used to determine the chip within a time-frame within which the modulated pulses are transmitted. Thus, the output of this block consists of sequence of time-modulated fourth-order derivative Gaussian pulses, which is fed into an AWGN block to simulate channel effects.

The correlator receiver is set-up on the basis of Equations 11-15 as shown in Figure 2 below.

Figure 1: Simulated time-modulated UWB transmitter

Figure 2: The Correlator Receiver
The ‘Template Signal Generator’ block generates a signal that is the difference between the expected signal and its time shifted version, which is correlated against the incoming pulse sequence. The integrator block performs an ‘integrate and dump’ operation by integrating the product of sample values of template signal and the UWB pulse sequence, and resetting to zero after every bit period. The integrator output is compared against a threshold to determine the bit value.

Figure 3 below shows the complete simulation set-up

4 RESULTS

The model was tested by transmitting a sequence of 200 data bits through the AWGN channel, while the channel signal-to-noise (SNR) was reduced from 2dB to -10dB. Figure 4 is shows 4 UWB pulses at the transmitter output, representing the ‘spread’ sequence ‘1101’. From the figure, it can be observed that each pulse lasts for 0.5ns.
Figure 5 shows this same bit sequence at the output of the AWGN channel for an SNR of -2dB. From this figure it can be observed that the amplitude and phase relationships of the transmitted UWB pulses are completely lost as a result of the additive noise process. Furthermore, the amplitude range of the transmitted sequence has increased.

The receiver algorithm earlier discussed specifies that the channel corrupted signal can be recovered by implementing an integration operation after correlating the signal with a local template waveform. Figure 6 is a shows of the synchronized template waveform used in the correlation.
The output of the correlation stage is sent to an integrator. Figure 7 below shows the integrator output.

![Integrator Output](image)

Figure 7: Integrator output

It can be observed from this figure that the integration operation clusters the noisy signal amplitudes into specific time slots. This is directly attributable to the ‘integrate and dump’ characteristic which is critical for the correct reception of the original data sequence. From the receiver algorithm previously discussed, it is clear that this timing must be prearranged, as it is not extracted from the channel-corrupted signal. The hardware implementation of this step therefore demands extremely high precision timing. Furthermore, the maximum amplitude excursion of these ‘clusters’ at output of the integrator is several orders of magnitude less than the amplitude of the noisy channel output. This behaviour is typical of integrate and dump filters (Sharma, 2008). Bit decisions are reached by comparing the signal energy in these signal ‘clusters’ against a threshold.

To evaluate the performance of the TM UWB scheme, 13 simulation runs were undertaken to determine bit-error ratios (BER) for channel signal-to-noise ratios (SNR) ranging from 2dB to -10dB. The results are shown in Figure 8.

![SNR vs BER](image)

Figure 8: Plot of channel SNR against BER

From the figure it can be observed that the TM UWB scheme demonstrates a high level of robustness against AWGN. The plot shows that a degrading of SNR has no effect on the BER until the SNR is less than -6dB. Further, it is observed that an error rate of 2.5% can still be achieved without the use of error correction codes at a channel SNR of -10dB.
CONCLUSION

This model of TM UWB has been developed for a single-user scenario, devoid of multipath fading channel effects. Its focus has been on the performance of the scheme in the presence of additive interference in the form of AWGN, which could typically result from thermal agitation at the front-end of radio receivers. A simulation model has been developed in SIMULINK by direct translation of mathematical models for the transmission and reception of TM UWB. The BER results obtained show a bit-error rate of less than 2.5% for SNR above -10dB. These results suggest that AWGN is not a significant channel impairment to TM UWB communication links. Reliable high bit-rate TM UWB data transmissions are therefore possible in the presence of AWGN.

REFERENCES