An Ultra Wideband Impulse Radio Transceiver

Eduardo Cano
University of Limerick

21st June 2005

OUTLINE

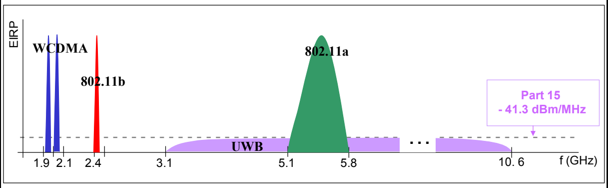
- INTRODUCTION TO UWB
- DIRECT SEQUENCE IMPULSE RADIO (DS-IR) SYSTEM
- M-ary BI-ORTHOGONAL TRANSCEIVER DESIGN
- SIMULATION ENVIRONMENT
- SIMULATION RESULTS
- CONCLUSIONS
- UWB IMPLEMENTATION

INTRODUCTION

- Definition of UWB. Regulatory Bodies: FCC (USA)/ ETSI (Europe)

Signal with Bandwidth > 500 MHz (or fractional bandwidth > 20%) in the band from 3.1 to 10.6 GHz with maximum PSD = -41.3 dBm/MHz (FCC Part 15)

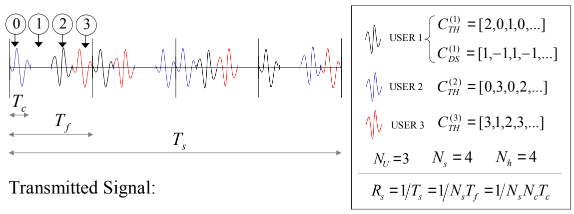
$$B_f = 2\frac{f_H - f_L}{f_H + f_L} = \frac{BW_{-3\text{dB}}}{f_c}$$



- Methods to generate UWB signals:
  - Single-band approach: Time Hopping, Direct Sequence or Direct Sequence Impulse Radio
  - Multi-band systems: Frequency Hopping/Multi-Carrier OFDM

DIRECT SEQUENCE IMPULSE RADIO (DS-IR)

- Concept:
  - Transmission of sub-nanosecond pulses.
  - The symbol time is divided into N_s frames. Each frame is composed of N_h slots.
  - Each user transmits N_s pulses per symbol (1 pulse per frame).
  - TH Code sequence assigns the corresponding slot and DS sequence gives the polarity



- Transmitted Signal:

$$s_{Tx}^{(k)}(t) = \sum_{j=-\infty}^{+\infty} A\beta_{\lfloor j/Ns \rfloor}^{(k)} C_{DS}^{(k)}(j) w_{Tx}(t - jT_f - C_{TH}^{(k)}(j)T_c - \delta d_{\lfloor j/Ns \rfloor}^{(k)})$$

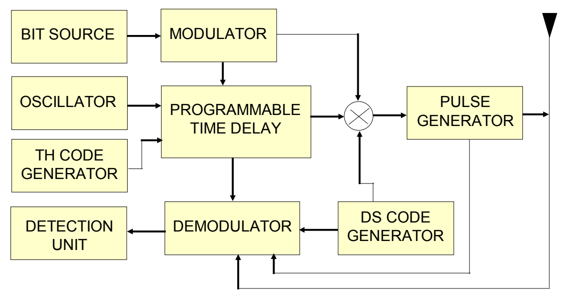
WHY DS-IR FORMAT?

- Power Spectral Density efficiency:
  - The TH spectral spikes are smoothed
  - The Transmitted PSD can be approximated by the PSD of the individual pulse
  - TH: $P_{Tx}(f) \cong P_s|W_{Tx}(f)|^2 N_s - P_s|W_{Tx}(f)|^2 \sum_{h,k=0}^{N_h-1} e^{-j2\pi(h-k)T_c f}\left[\frac{1}{N_h{}^2}\left(N_s + \sum_{h,k=0}^{N_s-1} e^{-j2\pi(h-k)T_f f}\right)\right]$
  - DS-IR: $P_{Tx}(f) \cong P_s|W_{Tx}(f)|^2 N_s$
- Increasing the number of "Orthogonal" Users
  - TH: $N_u = N_h$
  - DS-IR: $B \approx \frac{1}{T_w},\quad R_s = \frac{1}{T_s} = \frac{1}{N_s N_h T_c},\quad \frac{B}{R_s} \approx N_h N_s \longrightarrow N_u = N_s N_h$

Wireless Access Research

University of Limerick NCNRC

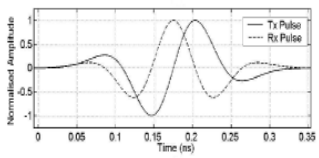
DS-IR TRANSCEIVER BLOCK DIAGRAM

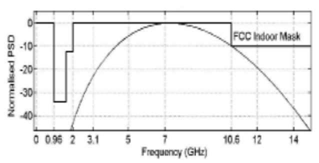


Wireless Access Research

University of Limerick NCNRC

TRANSMITTER PARAMETERS: PULSE SHAPE





- Tx pulse: 3rd derivative Gaussian pulse
- Rx pulse: 1st derivative of the Tx pulse
- Equations:

$$w_{Tx}(t) = \frac{A}{\sqrt{2\pi}}\left(\frac{3t}{\sigma^5} - \frac{t^3}{\sigma^7}\right)\exp\left(\frac{-t^2}{2\sigma^2}\right)$$

$$|W_{Tx}(f)| = A(2\pi f)^3 \exp\left(\frac{-(2\pi f\sigma)^2}{2}\right)$$

$$T_w = 0.36 \text{ ns} \iff \sigma = 38.1 \text{ ps}$$

$$f_c = \frac{\sqrt{3}}{2\pi\sigma} = 7.23 \text{ GHz}$$

Wireless Access Research

University of Limerick NCNRC

TRANSMITTER PARAMETERS: TH/DS CODE SEQUENCE

- TH/DS Code properties
  - Robustness against Multiple Access Interference
  - Smoothness of the PSD signal: Reduce the spectral spikes.
  - Random factor: LPD/LPI
  - Reduce interference with other wireless systems.
- Types of codes:
  - Ideal random orthogonal codes $N_u \le N_h N_s$
  - Pseudo-random code sequences:

    ML codes, Gold sequences, Barker codes, Kasami sequences, etc.
  - Orthogonal Codes: Walsh-Hadamar constructions, etc.

Wireless Access Research

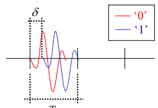
University of Limerick NCNRC

TRANSMITTER PARAMETERS: MODULATION SCHEMES (I)

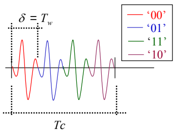
$$s_{Tx}^{(u)}(t) = \sum_{j=-\infty}^{+\infty} A\beta_{\lfloor j/Ns \rfloor}^{(k)} C_{DS}^{(k)}(j) w_{Tx}(t - jT_f - C_{TH}^{(k)}(j)T_c - \delta d_{\lfloor j/Ns \rfloor}^{(k)})$$

1) M-ary Pulse Position Modulation (M-PPM)

Example: Optimum 2-PPM



Example: Orthogonal 4-PPM

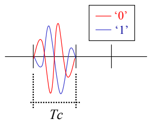


$$\beta_{\lfloor j/Ns \rfloor}^{(k)} = 1$$

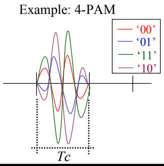
$$\delta d_{\lfloor j/Ns \rfloor}^{(k)} = 0, \delta, 2\delta, \ldots, (M-1)\delta$$

2) M-ary Pulse Amplitude Modulation (M-PAM)

Example: 2-PAM (BPSK)



Example: 4-PAM

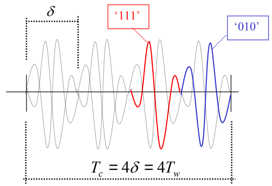


$$\beta_{\lfloor j/Ns \rfloor}^{(k)} = 2m - 1 - M \quad (m = 1,..,M)$$

$$\delta d_{\lfloor j/Ns \rfloor}^{(k)} = 0$$

TRANSMITTER PARAMETERS: MODULATION SCHEMES (II)

3) M-ary Bi-Orthogonal Modulation (M-BM): BPSK + M/2 - PPM



Example: 8-BM: BPSK + 4-PPM

$\vec{b} = \{1, 1, 1, 0, 1, 0, \ldots\}$

BPSK 4-PPM

First Symbol $k = 0$:

$\beta_{i=0}^{(1)} = 2\vec{b}(0) - 1 = 1$

$\vec{b}_{k,0} = [1,1]; \quad d_0^{(1)} = G(\vec{b}_{k,0}) = 2$

Second Symbol $k = 1$:

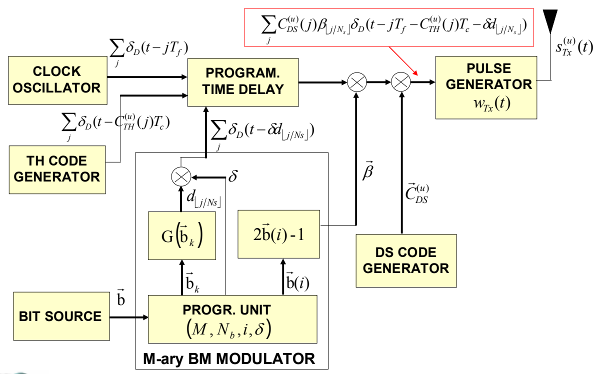
$\beta_{i=0}^{(1)} = 2\vec{b}(4) - 1 = -1$

$\vec{b}_{k,1} = [1,0]; \quad d_1^{(1)} = G(\vec{b}_{k,1}) = 3$

$$\beta_k^{(u)} = 2\vec{b}(k\log_2 M + 1) - 1 \qquad k = 0,1,2,\ldots,\frac{N_b}{\log_2 M} - 1$$

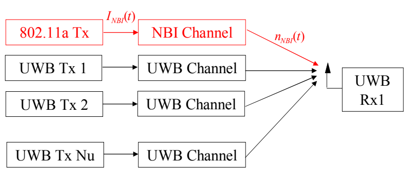
$$d_k^{(u)} = G(\vec{b}_k) \qquad \vec{b}_k = \left[\vec{b}(k\log_2 M + 2), \ldots, \vec{b}((k+1)\log_2 M)\right]$$

DS-IR TRANSMITTER USING M-ary BM



RECEIVED SIGNAL

$$r^{(1)}(t) = \underbrace{\sum_{i=1}^{L_P} \alpha(t,\tau_i^{(1)}) s_{Rx}^{(1)}(t - \tau_i^{(1)})}_{\text{Desired signal}} + \underbrace{\sum_{u=2}^{Nu}\sum_{i=1}^{L_P} \alpha(t,\tau_i^{(u)}) s_{Rx}^{(u)}(t - \tau_i^{(u)})}_{\text{Multiple Access Interference}} + \underbrace{n_{NBI}(t)}_{\text{NBI}} + \underbrace{n(t)}_{\text{AWGN}}$$



- Narrowband Interference

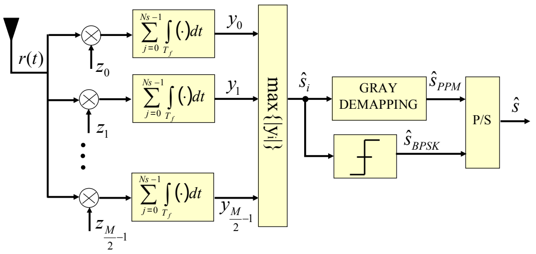
$$I_{NBI}(t) = \Re\left\{\left[\sum_{i=1}^{N_b}\sum_{k=-N/2}^{N/2} d_{k,j} e^{jk\frac{2\pi}{T}(t - iT_s)} p(t - iT_s)\right] e^{j2\pi f_c t}\right\}$$

- Multipath fading channel

$$h^{(u)}(t,\tau) = \sum_{i=1}^{L_P} \alpha(t,\tau_i^{(u)})\delta_D(t - \tau_i^{(u)})$$

BANK OF CORRELATORS RECEIVER

- The Bank of Correlators receiver is optimum when AWGN is the only distortion phenomenon
- The M-BM Receiver is formed by M/2 correlator units

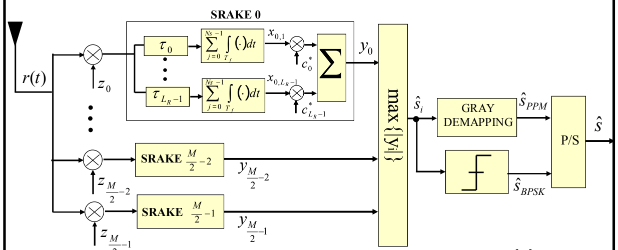


$$z_i^{(1)} = \sum_j C_{DS}^{(1)}(j)\, w_{Rx}(t - jT_f - C_{TH}^{(1)}(j)T_c - i\delta)$$

$$\hat{s}_i = \max\{y_i\} = \max\left\{\sum_{j=0}^{N_s-1}\int_{iT_b-jT_f}^{iT_b-(j+1)T_f} r(t)\, z_i^{(1)}(t)\right\} \qquad \begin{cases} \hat{s}_{BPSK} = \mathrm{sign}\{\hat{s}_i\} \\ \hat{s}_{PPM} = \mathrm{GD}\{\hat{s}_i\} \end{cases}$$

CONVENTIONAL RAKE RECEIVER

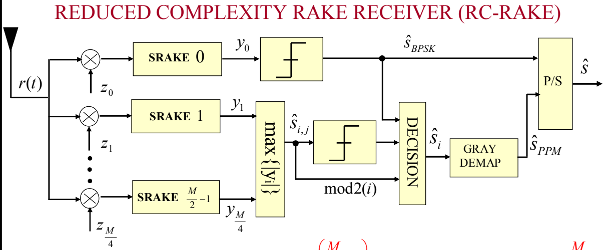
- RAKE receiver gathers the multipath energy



$$\hat{s}_i = \max\{y_i\} = \max\left\{\sum_{m=1}^{L_R-1} c_m * \left\{\sum_{j=0}^{N_s-1}\int_{iT_b-jT_f-\tau_m}^{iT_b-(j+1)T_f-\tau_m} r(t)\, z_i^{(1)}(t-\tau_m)\right\}\right\} \qquad \begin{cases} \hat{s}_{BPSK} = \mathrm{sign}\{\hat{s}_i\} \\ \hat{s}_{PPM} = \mathrm{GD}\{\hat{s}_i\} \end{cases}$$

- RAKE unit combining weights:
  - MRC: $c = \beta = [\alpha_0, \alpha_1, ..., \alpha_{L-1}]$
  - MMSE: $c = R_n^{-1}\beta^T$ $\quad R_n \approx \frac{N_0}{2} R_v(0)\left(I + 2\frac{N_i}{2}\frac{|V(F_c)|^2 BW_{NBI}}{R_v(0)} Re\{zz^H\}\right)$

REDUCED COMPLEXITY RAKE RECEIVER (RC-RAKE)



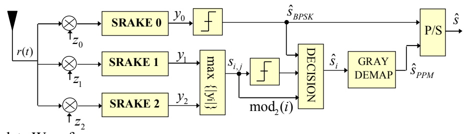
- Total Number of Correlators: RC-RAKE: $NC = \left(\frac{M}{4}+1\right)L_R$; Conventional-RAKE: $NC = \frac{M}{2}L_R$
- Template Waveform Definition: $z_i^{(1)} = \sum_j C_{DS}^{(1)}(j)\,\phi_i(t - jT_f - C_{TH}^{(1)}(j)T_c)$
  - BPSK bit detection

    $$\phi_0 = \sum_{j=0}^{M/2-1} w_{Rx}(t - j\delta)$$

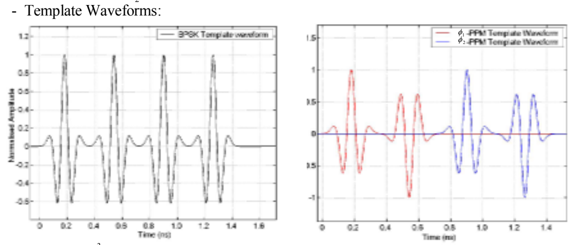
  - PPM bits detection:

    $$\phi_i = w_{Rx}(t - 2(i-1)\delta) - w_{Rx}(t - (2i-1)\delta) \ ; \quad i = 1,2,..,\frac{M}{4}$$

EXAMPLE: 8-BM SCHEME (I)

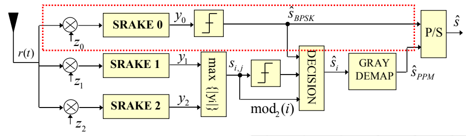


- Template Waveforms:



$$\phi_0 = \sum_{j=0}^{3} w_{Rx}(t - j\delta) \qquad \phi_1 = w_{Rx}(t) - w_{Rx}(t-\delta) \qquad \phi_2 = w_{Rx}(t-2\delta) - w_{Rx}(t-3\delta)$$

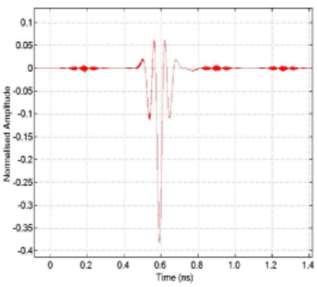
EXAMPLE: 8-BM SCHEME (II)



1) BPSK Bit Detection:

- Transmitted symbol '001'

-Resulting signal after matching a received pulse and BPSK Template waveform ϕ_0 ➡

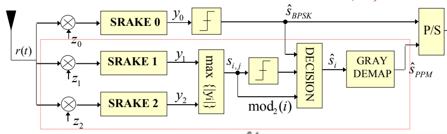


$$z_0^{(1)} = \sum_j C_{DS}^{(1)}(j)\phi_0(t - jT_f - C_{TH}^{(1)}(j)T_c)$$

- After summing all the N_s pulse contributions belonging to the same symbol and combining all the L_R multipaths:

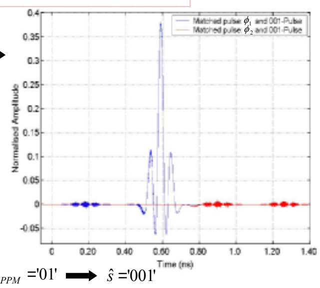
$$\hat{s}_{BPSK} = \begin{cases} 0 & \text{if } y_0 \le 0 \\ 1 & \text{if } y_0 > 0 \end{cases}$$

EXAMPLE: 8-BM SCHEME (III)



2) 4-PPM Bits Detection:

- Resulting signal after matching a received pulse and PPM Template waveforms ϕ_1 , ϕ_2 ➡



- Decision: $\hat{s}_{i,j} = \max\{|y_i|\} = \begin{cases} '00' \\ '01' \end{cases}$

$$\text{last bit} \begin{cases} 0 \text{ if } \begin{cases} \text{mod}(i,2) = 1; & \hat{s}_{BPSK} = 0; & \hat{s}_{i,j} < 0 \\ \text{mod}(i,2) = 1; & \hat{s}_{BPSK} = 1; & \hat{s}_{i,j} > 0 \\ \text{mod}(i,2) = 0; & \hat{s}_{BPSK} = 0; & \hat{s}_{i,j} > 0 \\ \text{mod}(i,2) = 0; & \hat{s}_{BPSK} = 1; & \hat{s}_{i,j} < 0 \end{cases} \\ 1 \text{ else} \end{cases}$$

Example:

$\text{mod}(1,2) = 1;\ \hat{s}_{BPSK} = 0;\ \hat{s}_{i,j} > 0$ ➡ $\hat{s}_{PPM}$ ='01' ➡ $\hat{s}$ ='001'

MOTIVATIONS FOR USING M-BM: BER and CAPACITY

- Bit Error Rate: MAI + AWGN *

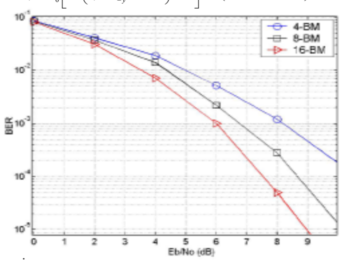
$$P_e = \frac{M/2}{M-1} \int_0^{+\infty} p(e/x) p_{\eta_s}(x) dx \qquad p(e/\eta_s) = \frac{1}{\sqrt{2\pi}} \int_0^{+\infty} \left[1 - \left(\frac{1}{\sqrt{2\pi}} \int_{-y}^{+y} e^{-x^2/2} dx \right)^{M/2-1} \right] \exp\left(-\frac{1}{2} \left(y - \sqrt{2\eta_s} \right)^2 \right) dy;$$

chi-squared f.d.p:

$$p_{\eta_s}(x) = \frac{1}{(\tilde{\eta}_s)^{L/2} \Gamma(L/2)} x^{L/2-1} e^{-x/\tilde{\eta}_s}$$

SNR symbol:

$$\eta_s = \frac{(\tilde{N}_s E_w)^2}{N_0 \tilde{N}_s E_w + \tilde{N}_s (N_u - 1) R_w^2} \sum_{l=0}^{L-1} \left(\alpha_{N_s,l}^{(1)} \right)^2$$



- Capacity:

The system capacity increases when M increases

* Ishiyama Y. et al. "*Performance Analysis of UWB-IR Systems with Multiple Modulations*". 2003

SIMULATION PARAMETERS AND ASSUMPTIONS

- Antennas are modeled as derivative unit of the pulses
- Perfect synchronization and channel estimation at the receiver.
- Asynchronous delay between users.
- DS-IR parameters:

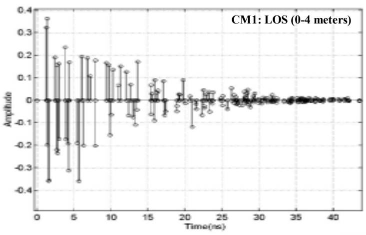
$R_b(Mbps)$	110
$T_w(ns)$	0.36
N_u	8
N_h	8
$\delta(ns)$	0.36

$T_c(ns)$	$T_w + \left(\frac{M}{2} - 1\right)\delta$
$T_f(ns)$	$N_h T_c$
N_s	$\lfloor \log_2 M / R_b T_f \rfloor$

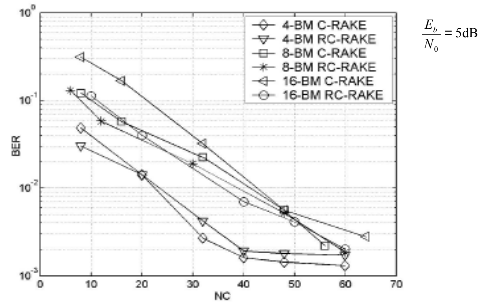
Channel Model	IEEE 802.15.3a CM1 (LOS 0-4m)
TH Code	Ideal Orthogonal Random Codes
DS Code	Walsh-Hadamard Codes
SRAKE	No NBI and MRC weights

SIMULATION PARAMETERS: IEEE 802.15.3A CHANNEL

CHANNEL	LOS/NLOS	Distance Tx-Rx	RMS Delay Spread	Mean excess delay	NP (85%)
CM 1	yes	0-4 m	5.28 ns	5.05 ns	24
CM 2	no	0-4 m	8.03 ns	10.38 ns	36.1
CM 3	no	4-10 m	14.28 ns	14.18 ns	61.54
CM 4	no	> 10 m	25 ns	—	—



SIMULATION RESULTS

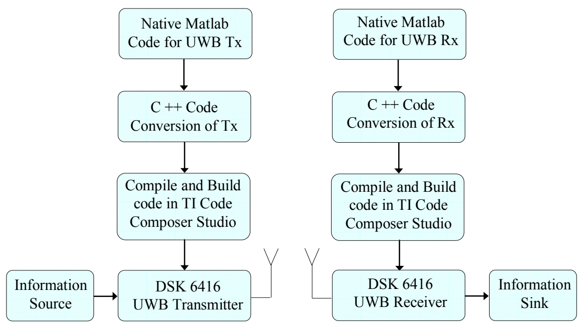


- Conventional-RAKE (C-RAKE): $NC = \frac{M}{2} L_R$
- Reduced Complexity-RAKE (RC-RAKE): $NC = \left(\frac{M}{4}+1\right) L_R$

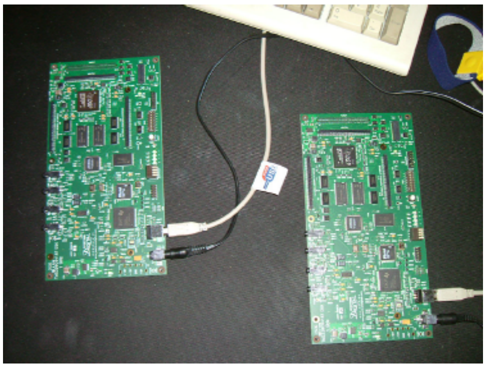
CONCLUSIONS

- Properties of DS-IR Systems: Spectral Efficiency and Increase of the Nu
- DS-IR Transmitter Design for M-BM scheme
- Advantages of Using M-ary Bi-Orthogonal scheme:
  - Increased Capacity
  - Increased Multiple Access Performance
- High Complexity when M is large
- Reduced Complexity RAKE Structure
  - Complexity reduction by means of new definition of Template pulses.
  - The number of correlation functions is reduced to $NC = \left(\frac{M}{4}+1\right) L_R$ instead of $NC = \frac{M}{2} L_R$
  - The RC-RAKE design is more susceptible to pulse shape distortion: Template signal estimation is required to improve BER performance.

UWB HARDWARE IMPLEMENTATION BLOCK DIAGRAM



UWB TRANSMITTER AND RECEIVER PROCESSORS



THANK YOU