Waveform Design, Channel Estimation and Multiple Access for UWB Radios

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Outline

- Optimal UWB pulse shapers
- Timing synchronization for UWB
- UWB channel estimation
- UWB multiple access
- Summary
Baseband UWB

![Graph showing baseband UWB signals: Gaussian pulse (GP), 1st derivative of GP, 2nd derivative of GP.](image)

Baseband UWB vs. FCC Mask

![Graph comparing baseband UWB to FCC mask.](image)

- **System 1**: 
  - ✅ to maximize Tx power, G-monocycle
  - ✗ violates the FCC spectrum mask

- **System 2**: 
  - ✅ to respect the FCC mask, G-monocycle
  - ✗ does not exploit the mask efficiently

**SPinCOM University of Minnesota**
Should we go Baseband ? Single band?

- **Pros:**
  - carrier-free \( \Rightarrow \) low-cost RF components
  - low duty-cycle \( \Rightarrow \) prolonged battery life
  - low power \( \Rightarrow \) covert communications

- **Cons:**
  - single band inflexible with narrowband interference (NBI)
  - power-inefficient use of FCC mask

Better Pulse-Shapers?

- **Gaussian monocycle:**
  - does NOT optimally exploit FCC mask
  - does NOT avoid interference with co-existing RF systems
  - does NOT facilitate Frequency-Hopping (FH) to gain LPI-LPD

- **Possible alternatives:**
  - analog filtering of the G-monocycle \( \Rightarrow \) lacks flexibility & repeatability
  - carrier-modulation of the G-monocycle \( \Rightarrow \) carrier frequency offset/jitter
Optimal Pulse-Shapers for UWB

Idea: digitally filter the antenna generated pulse \( g(t) \) [LYG’03]

\[
p(t) = \sum_{k=0}^{M-1} w[k] g(t - kT_0)
\]

Step 1: Select digital filter tap spacing \( T_0 \)
Step 2: Find \( M \) tap coefficients \( \{w[m]\}_{m=0}^{M-1} \), so that:

\[
|W(e^{2\pi f})| := \left| \sum_{m=0}^{M-1} w[m] e^{-2\pi fmT_0} \right| \approx \begin{cases} 
P_d(f), & f \in [0, \frac{1}{2T_0}] \\ 
\mathcal{M}(f), & f \in \left[\frac{1}{2T_0}, +\infty\right] 
\end{cases}
\]

\( P_d(f) \): desired FT magnitude
\( \mathcal{M}(f) \): normalized sqrt (ERIP FCC mask)

Algorithm and Implementation

- Solution: **Parks-McClellan** digital filter design algorithm
- Optimality: \( \{w[m]\}_{m=1}^{M} = \arg \min \{w[m]\}_{m=1}^{M} \{ \max_{F \in \mathcal{F}} |e(F)| \} \)

\( \mathcal{F} \in [0, 0.5] : \bigcup \) prescribed disjoint intervals

\( e(F) = \lambda(F) \left| W(e^{2\pi f}) - D \left( \frac{f}{f_0} \right) \right| : \) weighted error

- Implementation:
**Single-Band UWB: Example I**

- G-monocycle with $T_p = 0.37\text{ns}$
- Select $T_0 = 35.7\text{ps}$ to gain full control over $0$ to $10.6\text{GHz}$
- Design $\{w[m]\}_{m=0}^{M-1}$, $M=33$

![Graphs showing amplitude and frequency response for Example I](image)

**Pulse Duration $1.3\text{ ns}$**

Maximum Power $0.91\text{ mW}$

Optimal approximation over the entire bandwidth

High clock rate

---

**Single-Band UWB: Example II**

- G-monocycle with $T_p = 0.37\text{ns}$
- Select $T_0 = 73\text{ps}$ to exploit the symmetry
- Design $\{w[m]\}_{m=0}^{M-1}$, $M=33$

![Graphs showing amplitude and frequency response for Example II](image)

**Pulse Duration $2.4\text{ ns}$**

Maximum Power $0.88\text{ mW}$

Sub-optimal approximation over the entire bandwidth

Lower clock rate
Comparison I: Maximum Tx Power

- A & B: Gaussian monocycles
- C: pulse shaper in [Parr et al. '03]
- D & E: pulse shapers in [LYG'03]

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration (ns)</td>
<td>0.37</td>
<td>0.19</td>
<td>1.3</td>
<td>2.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Tx power (µW)</td>
<td>0.506</td>
<td>3.43</td>
<td>250</td>
<td>880</td>
<td>910</td>
</tr>
</tbody>
</table>

Multi-Band UWB: Example

- G-Monocycle with $T_p = 0.37\text{ns}$
- Select $T_0 = 35.7\text{ps}$ to gain full control over 0~10.6GHz
- For the $n$th sub-band, design $\{w_n[m]\}_{m=0}^{M-1}$ such that:

$$
\sum_{m=0}^{M-1} w_n[m] e^{-2\pi f_m T_0} \approx \begin{cases} 
0 & f \in [0, 3.1 + n \cdot \frac{7.5}{N}] \text{GHz} \\
\frac{P(D)}{P(R)} & f \in [3.1 + n \cdot \frac{7.5}{N}, 3.1 + (n + 1) \cdot \frac{7.5}{N}] \text{GHz} \\
0 & f \in [3.1 + (n + 1) \cdot \frac{7.5}{N}, 10.6] \text{GHz}
\end{cases}
$$

- Tradeoffs:
  - $T_0 \uparrow \Rightarrow$ complexity ↓, number of independent sub-bands ↓
  - number of sub-bands $\uparrow \Rightarrow$ complexity ↑, flexibility ↑
Carrier-Free Multi-Band UWB

- Attractive features:
  - Optimal FCC mask exploitation
  - Flexible NBI avoidance
  - Baseband FH

- Implementation:

![Diagram of Carrier-Free Multi-Band UWB implementation](image)

Comparison II: Average BER

- In the absence of NBI
- In the presence of NBI

Narrowband interference between 0.99GHz and 3.1 GHz, Power of NBI is 10 times AWGN variance
Timing Synchronization for UWB

\[ v(t) = \sqrt{E} \sum_{n=-\infty}^{\infty} s((n/N_f)\Delta) p(t - nT_f - c(n)T_c) \]

\[ r(t) = \sum_{i=0}^{L} a_i v(t - \tau_{i0} - \tau_0) + \text{noise} \]

- First arrival time \( \tau_0 \)
- Timing synchronization: finding \( \tau_0 \)
- **Acquisition**: coarse timing
- **Tracking**: fine timing

Prior Art

- Coarse bin reversal search in the absence of noise  
  [Homier-Scholtz’02]
- Coded beacon sequence in the absence of multipath  
  [Fleming’02]
- Ranging system requiring strongest path knowledge  
  [Lee-Scholtz’02]
- Non-data aided timing for UWB in dense multipath  
  [Yang-Tian-Giannakis’02]
- Data-aided Generalized Likelihood Ratio Tests (GLRT)  
  [Tian-Giannakis’03]
Timing with a Clean Template (1)

- When multipath is absent but TH is present

\[ T_s = N_f T_f \]

Need to search \( T_s / T_p \) (> 1,000) bins

Timing with a Clean Template (2)

- When multipath is also present

\[ T_s = N_f T_f \]

✓ Tracking possible with fast TH [H-S'02,T-Y-G'02]

✗ Acquisition only with slow/no TH [Yang-Tian-GG'03, Tian-GG'03]

✗ Poor energy capture ⇒ synchronization performance affected
If we knew the channel …

⇒ Maximum Likelihood (ML) & sub-opt. Early-Late gate

Idea: Timing with “Dirty” Templates (TDT)!

“Dirty” Templates

- Aggregate pulse: \( p_R(t) = \sum_{l=0}^{L} \alpha_{l} r(t - \tau_{0,l}) \)

- Rx waveform: \( r(t) = \sqrt{E} \sum_{k=\infty}^{\infty} s(k) p_R(t - kT_s - \tau_0) + noise \)

- “Dirty” Templates:
  \[ r(l \in [0, T_s)) \quad r(t + (k-1)T_s + \tau) \quad r(t + kT_s + \tau) \]
Our Key Observation

Symbol-rate samples:
\[ x_k(\tau) = \int_0^{T_s} r(t + (k-1)T_s + \tau) r(t + kT_s + \tau) dt, \quad \forall \tau \in [0, T_s] \]

Cauchy-Schwartz's inequality (noise absent):
\[ \|x_k(\tau)\|^2 \leq \int_0^{T_s} r^2(t + (k-1)T_s + \tau) dt \int_0^{T_s} r^2(t + kT_s + \tau) dt \]

Equality holds \( \forall k \) iff
\[ r(t + (k-1)T_s + \tau) = \lambda r(t + kT_s + \tau), \quad \forall \tau \in [0, T_s) \iff \tau = 0 \]

Timing with “Dirty” Templates (TDT)

**Theorem** [Yang-GG'03,04]: Consistent timing offset estimation can be accomplished in the absence of ISI even when TH codes are present and the UWB multipath is unknown, using “dirty” Ts-long segments of the received waveform as follows:

\[ t_0 = \arg \max_{\tau \in [0,T_s]} \frac{1}{K} \sum_{k=1}^{K} \left( \int_{-T_s/2}^{T_s/2} r(t + \tau) r(t + \tau - T_s) dt \right)^2 \]
The Beauty of the Training Pattern

Training Pattern: \( \ldots \, s, -s, -s, s, s, -s, -s, \ldots \)

\[ x_k(r) = (-1)^k s^2 [E_B(r_0 - r) - E_A(r_0 - r)] + \xi(k) \]

- \( K^{-1} \sum_{k=1}^{K} x_k^2(r) \) converges faster to
  \[ \mathbb{E}(x_k^2(r)) = s^4 [E_B(r_0 - r) - E_A(r_0 - r)]^2 + \sigma_k^2 \]

- \( K=1 \) pair suffices \( \Rightarrow \) rapid acquisition
- Enables multi-user TDT

Why is this result neat?

- A distinct criterion for timing synchronization:
  - Auto-correlation vs. Cross-correlation
  - Clean vs. Dirty templates and the noise-noise issue

- Features:
  - TDT with both training and blind modes
  - Simple integrate-and-dump operations
  - Acquisition and tracking at any desirable resolution!
  - With or without TH & With or without multipath
  - VCC implementation possible
**TDT Acquisition: Blind Mode**

- $N_f = 32$
- $N_e$ uniform over $[0, N_f - 1]$

<table>
<thead>
<tr>
<th>Dirty template:</th>
<th>Clean $p(t)$ template:</th>
</tr>
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</table>

- Good energy capture $\Rightarrow$ good performance
- Simple integrate-and-dump operations $\Rightarrow$ low complexity

**TDT Acquisition: Training Mode**

- $N_f = 32$
- $N_e$ uniform over $[0, N_f - 1]$

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<tr>
<th>Synchronization MSE:</th>
<th>Detection BER:</th>
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</table>

- Data-aided TDT operational with $K=1$ $\Rightarrow$ rapid acquisition
- Considerable BER improvement
**TDT in Multi-User Settings**

- Two interfering asynchronous users

### Timing acquisition MSE:

- Rapid acquisition in ad hoc networks
- Operational without modification
- Improvement possible

### BER performance:

- No timing acquisition
- Perfect timing
- With timing acquisition

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**Channel Estimation**

- Needed for Rake reception

**Q:** Can we estimate the baseband-equivalent sampled channel?

- Pulse duration $T_p = 0.7ns$ $\Rightarrow$ sampling rate 14.3-35.7GHz

  - Lottici et al '02 samples 10-25 times per pulse

**A:** Only for sub-band channels in "multi-band UWB"
Transmitted Reference (TR)

**Tx:** \( v(t) = p(t) + s \cdot p(t - T_f), \quad s = \{ \pm 1 \} \)

\[ 
\begin{array}{c}
\text{Pilot waveform} \\
\text{Modulated waveform}
\end{array}
\]

**Rx:** \( r(t) = h(t) + s \cdot h(t - T_f), \quad h(t) := \sum_{\tau=0}^{L} \alpha p(t - \tau) \)

\[ 
\begin{array}{c}
\text{Pilot waveform} \\
\text{Modulated waveform}
\end{array}
\]

**Idea:** Rx pilot waveform as correlator template [Hoctor-Tomlinson’02]

\[ 
\hat{s} = \text{sign} \left\{ \int r(t) r(t - T_f) dt \right\} = \text{sign} \left\{ s \int h^2(t) dt \right\} = s
\]

Pilot Waveform Assisted Modulation (PWAM)

**Tx:**

\[ 
\begin{array}{c}
\text{pilot waveforms} \\
\text{info. conveying waveforms}
\end{array}
\]

**Rx:**

\[ 
\begin{array}{c}
\text{Analog Delay Element} \\
\text{Analog Delay Element}
\end{array}
\]

- PWAM [Yang-GG’02]
  - Error performance similar to differential decoding
  - Low complexity (just frame-rate integrate-and-dump)
  - Performance-rate tradeoffs, and robustness to timing jitter
**PWAM Optimality**

**Theorem [Yang-GG’02]:** Given $T_f$, $N_f$, and channel coherence time $\tau_e$, equi-spaced pilot waveforms every $\lfloor \tau_e/T_f \rfloor$ pulses, and equi-powered with $E_{\text{avg}} [N_f/(\sqrt{\tau_e/T_f} - N_f + \sqrt{N_f})]$ achieve the channel CRLB and maximize average capacity.

---

**PWAM Relatives**

- **Transmitted reference (TR) signaling [Hoctor-Tomlinson’02, Choi-Stark’02]:**
  
  When $N = 2N_f$, PWAM yields:
  
  - Optimal number of pilot waveforms: $N_p = N_f$
  - Optimal energy allocation factor: $\alpha = \frac{1}{2}$
  
  $\Rightarrow$ **TR is optimal only when $N = 2N_f$**

- **Pilot symbol assisted modulation (PSAM) [Cavers’91, Ohno-Giannakis’02]:**
  
  - discrete-time channel taps vs. continuous-time channel waveform (pulse-rate sampling vs. frame-rate integrate-and-dump)
  - narrowband with inter-symbol interference (ISI) vs. UWB without ISI
  - one digital pilot symbol vs. multiple analog pilot pulses across frames
Placement of Pilot Waveforms

- PWAM with distributed pilot waveforms:

- Transmitted reference: special case of PWAM when \( N = 2N_f \)

- Preamble:

Equi-SNR (ES-)PWAM

- Nominal SNR:
  \[ \rho = \frac{N_f E_s}{N \sigma^2} \]

- Information SNR:
  \[ \rho_i = \frac{E_s}{N_i \sigma^2} = \frac{N}{N_s N_f} \alpha \rho \]

- Pilot SNR:
  \[ \rho_p = \frac{N_f E_p}{N_p \sigma^2} = \frac{N}{N_p} (1 - \alpha) \rho \]

- Facilitates operation of nonlinear power amplifiers
- Reduces interference to existing NB systems
Average Capacity and Performance

- Average capacity
- BER in peer-to-peer and multiple access

TR vs. PWAM vs. Preamble

At high SNR: 250 Kbps (TR) 495 Kbps (N=100) 499 Kbps (N=500)

Types of channels:
- Quasi-static: PWAM outperforms TR, and offers higher rate
- Time-varying: PWAM outperforms preamble
Baseband Modulation for UWB

- Pulse Position Modulation (PPM)
- Pulse Amplitude Modulation (PAM)

Each symbol is conveyed by $N_f$ pulses $p(t)$

$$T_s = N_f T_f$$

UWB Multiple Access

- Time Hopping (TH):
  $$v_n(t) = \sqrt{E_a} \sum_{n=\infty}^{\infty} s_n((n/N_f))p(t - nT_f - e_0(n)T_e) \quad [Scholtz '93]$$

- Direct Sequence (DS):
  $$v_n(t) = \sqrt{E_a} \sum_{n=-\infty}^{\infty} s_n((n/N_f))e_0(n)p(t - nT_f) \quad [Foerster '03]$$

DS code for User A: 1 1 1 1

DS code for User B: 1 -1 1 -1
Baseband UWB-MA

- Tx signal of user $u$:
  $$v_u(t) = \sqrt{\xi_u/N_f} \sum_{k=0}^{\infty} s_u((k/N_f))c_0(k)p(t - kT_f - c_0^h(k)T_c)$$

- Existing codes:
  - TH-UWB:  $c_0^h(k) \in [0, [T_f/T_c]]$, and $c_0(k) = 1$, $\forall k$
  - DS-UWB:  $c_0(k) \in \{\pm 1\}$, $\sum_{k=0}^{N_f-1} c_0^2(k) = N_f$, and $c_0^h(k) = 0$, $\forall k$

- Features:
  - ✓ constant modulus
  - ✓ not flexible in handling narrow-band interference (NBI)
  - ✓ not flexible in handling multi-user interference (MUI)

Baseband Single/Multi-Carrier UWB-MA

- $N_u = N_f$ real orthogonal subcarriers:
  - Set I with $f_{u} = (u + 0.5)/N_f$, $\forall u \in [0, N_f - 1]$
    $$[f_{u}]_k = \begin{cases} \sqrt{2} \cos(2\pi f_{u} k), & u = 0, \text{ or } u = \frac{N_f}{2} \\ \sqrt{2} \sin(2\pi f_{u} k), & u \in \left[\frac{N_f}{2}, N_f - 1\right] \end{cases}, \forall k \in [0, N_f - 1]$$
  - Set II with $f_{u} = u/N_f$, $\forall u \in [0, N_f - 1]$
    $$[f_{u}]_k = \begin{cases} \cos(2\pi f_{u} k), & u = 0, \text{ or } u = \frac{N_f}{2} \\ \sqrt{2} \cos(2\pi f_{u} k), & u \in \left[\frac{N_f}{2}, N_f - 1\right] \end{cases}, \forall k \in [0, N_f - 1]$$

- Baseband single- and multi-carrier (SC/MC) user codes:
  $$c_u = \sum_{k=1}^{N_f-1} [c_u^{(\phi)}]_k f_k$$

- $\{c_u^{(\phi)}\}_{\phi=0}^{N_f-1}$ spreading codes
  - ✓ generally MC; SC if $c_0^{(\phi)} = c_0$, $\forall u$
Multi-Band Transmission

- Discrete cos/sin functions $\Rightarrow$ DCT implementation & one RF chain!
- Digital carriers $\Rightarrow$ flexibility in handling NBI
- Multiband transmission full multipath diversity even with SC!

Discrete cos/sin functions $\Rightarrow$ DCT implementation & one RF chain!
- Digital carriers $\Rightarrow$ flexibility in handling NBI
- Multiband transmission full multipath diversity even with SC!

MC-UWB vs. DS-UWB

- $\tau_L = 90\text{ns}$, $T_f = 24\text{ns} \nLeftarrow$ IFI
- $L_R = 2$, $N_f = 32$, $T_R \approx 1.0\text{ns}$
- ISI avoided by:
  - zero-padding (ZP)
  - cyclic-prefix (CP)
- Saleh-Valenzuela Channel Model
  $$\left(\frac{1}{\lambda}, \frac{1}{\lambda}, \Gamma, \gamma\right) = (2, 0.5, 30, 5)\text{ns}$$
- Benchmarks generated using MRC (in the absence of IFI)

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<thead>
<tr>
<th></th>
<th>MC-UWB</th>
<th>DS-UWB</th>
</tr>
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<tbody>
<tr>
<td>Code-indep</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>
**CP vs. ZP**

- CP for ISI removal, MF-RAKE
- ZP for ISI removal, MF-RAKE

- MC > SC ≈ DS > MC’
- MC > DS > MC’ ≈ SC

> MC-UWB achieves maximum diversity AND maximum coding gains

---

**Comparison: Multiple Access**

- CP for ISI removal, MF-RAKE

Dotted curves (low load):
- $N_d = 1$

Solid curves (medium load):
- $N_d = N_f/2 + 1 = 17$

> SC-UWB achieves better MA performance with simple MF-RAKE

---
**NBI and AWGN**

- MC-UWB enables user-independent performance
- MC-UWB yields best BER
- SC-UWB similar to DS-UWB

![Graph showing BER performance with NBI and AWGN](image)

**NBI and Multipath**

- MC-UWB: user-independent performance
- MC-UWB outperforms DS-UWB

![Graph showing BER performance with NBI and Multipath](image)
Summary

- Optimal UWB pulse shapers:
  - Dynamic narrowband interference avoidance
  - Single-band or multi-band
  - Time-hopping and/or frequency-hopping

- Synchronization for UWB communications:
  - In the presence/absence of TH and/or multipath
  - Rapid acquisition with low complexity and good performance
  - Data-aided or blind, single-user or multi-user settings

- UWB channel estimation
  - Transmitted Reference (TR)
  - Optimal Pilot Waveform Assisted Modulation (PWAM)

- Baseband UWB radios
  - Baseband SC/MC codes for multiple access
  - Unifying model for comparison in the presence of NBI