Interference investigations within noncoherent multiband impulse radio UWB

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6th UWB Forum on Sensing and Communication, Graz, Austria, May 5, 2011
Overview

- Motivation, Multiband Impulse Radio UWB
- Interference Robustness of OOK/BPPM based Energy Detection
- Adaptive Coexistence using Image Processing
- Narrow- and Broadband Interference Mitigation

Dehner et al., „Multiband Impulse Radio – An Alternative Physical Layer for High Data Rate UWB Communication“, FREQUENZ, Band 63, Heft 9-10, September/Oktober 2009, S. 200-205.
Motivation, Multiband Impulse Radio UWB

- High data rate communication over short distances (e.g., 500 Mbit/s, 0 … 4 m, LOS/NLOS)

- Multiband Impulse Radio UWB (MIR UWB)
  - Low power, low complexity, low cost realization
  - High scalability and flexibility
  - Noncoherent receiver (energy detection)
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- Crucial issue of MIR UWB
  - No exclusive frequency ranges
  - Underlaying radio technology: high interference potential (e.g., IEEE 802.11a, other UWB systems, ...)
    - High susceptibility of non-linear receiver
    - Interference handling critical
Exemplary Interference Scenario

- MB OFDM UWB (IEEE 802.15.3a)
  1) MB OFDM UWB 1: band group A with TF-Code (1, 2, 3, 1, 2, 3)
  2) MB OFDM UWB 2: 2 bands in band group C with TF-Code (6, 7, 6, 7, 6, 7)
- WLAN (IEEE 802.11a), channel 44
Overview

- Motivation, Multiband Impulse Radio UWB
- **Interference Robustness of OOK/BPPM based Energy Detection**
- Adaptive Coexistence using Image Processing
- Narrow- and Broadband Interference Mitigation

Dehner et al., „Narrowband Interference Robustness for Energy Detection in OOK/PPM“, *IEEE Int. Conf. Commun. (ICC’10)*.
Dehner et al., „Narrow- and broadband Interference Robustness for OOK/BPPM based Energy Detection“, *accepted to IEEE Int. Conf. Commun. (ICC’11)*, Kyoto, Japan, June 2011.
Signal Model: Transmitter

- Binary data transmission within a subband of bandwidth $B$ located at carrier frequency $f_c$.

- Rectangular pulse of energy one ($f_c \gg 1/T_p$): $p(t) = \sqrt{2/T_p} \cos(2\pi f_c t), 0 < t < T_p$

- Transmitted signals for OOK/BPPM:
  \[ s_o(t) = \sqrt{E_p^O} \sum_{k=-\infty}^{\infty} b_k p(t - kT_b), \quad s_p(t) = \sqrt{E_p^P} \sum_{k=-\infty}^{\infty} p\left(t - kT_b - b_k \frac{T_b}{2}\right) \]

- Uniformly distributed data bit $b_k \in \{0, 1\}$ specified by bit energy $E_b$ and bit duration $T_b = T_p/d_s$ with duty cycle $d_s \leq 0.5$

- Modulation specific pulse energy $E_p^i, i \in \{O, P\}$: $E_p^O = 2E_p^P = 2E_b$
Signal Model: Receiver

Received signal \( y(t) = s_i(t) + n(t) + j(t), i \in \{O, P\} \) subjected to energy detection

Modeling noise \( n(t) \) and interference \( j(t) \) as band-limited wide-sense stationary, time-continuous zero mean Gaussian processes \( J(t) \) and \( N(t) \)

→ Autocorrelation functions \( (\tau = t_1 - t_2) \):

\[
R_N(\tau) = P_N \frac{\sin(\pi B \tau)}{\pi B \tau} \cos(2\pi f_c \tau) \\
R_J(\tau) = P_J \frac{\sin(\pi B_j \tau)}{\pi B_j \tau} \cos(2\pi f_j \tau)
\]

Passband noise signal depends on mean noise power \( P_N, B \) and \( f_c \).
Interference Parameters

\[ R_j(\tau) = P_j \frac{\sin(\pi B_j \tau)}{\pi B_j \tau} \cos(2\pi f_j \tau) \]

Remarks:
- Mean interference power \( P_j = E_{b,j} / T_{b,j} \) with interference bit energy \( E_{b,j} \) and bit duration \( T_{b,j} = q T_b, q > 0 \)
- Interference signal duration: \( T_{p,j} \approx 1 / B_j \leq T_{b,j} \)
- Interference duty cycle: \( d_j = T_{p,j} / T_{b,j} = d_s T_{p,j} / q T_p \)
- SIR_{in} at the input of energy detection: \( \text{SIR}_{in} = E_b / (T_b P_j) = ... = (d_s E_b) / (d_j T_p B_j E_{b,j}) \)
Signal Model: Energy Detection (OOK)

**OOK**

Asymmetric decision variable

\[
x^O = \int_0^{T_p} y^2(t) dt = x_s^O + x_{sjn}^O + x_{jn}^O
\]

\[
x_s^O = \begin{cases} 
0 & b_k = 0 \\
2E_b & b_k = 1
\end{cases}
\]

\[
E(x_s^O) = E_b, E\left((x_s^O)^2\right) = 2E_b^2
\]

\[
x_{jn}^O = \int_0^{T_p} (J(t) + N(t))^2 dt \
\]

\[
b_k = 0,1
\]

\[
x_{sjn}^O = \begin{cases} 
0 & b_k = 0 \\
\sqrt{8E_p^O/T_p} \int_0^{T_p} \cos(2\pi f_c t)(J(t) + N(t))dt & b_k = 1
\end{cases}
\]
Signal Model: Energy Detection (BPPM)

**BPPM**
Symmetric decision variable

\[
x^P = \int_0^{T_p} y^2(t) \, dt - \int_{T_b/2}^{T_p+T_b/2} y^2(t) \, dt = x_s^p + x_{jn}^p + x_{jn}^p
\]

\[
x_s^p = \begin{cases} E_b & b_k = 0 \\ -E_b & b_k = 1 \end{cases} \quad E(x_s^p) = 0, E\left((x_s^p)^2\right) = E_b^2
\]

\[
x_{jn}^p = x_{jn}^O - \int_{T_b/2}^{T_p+T_b/2} (J(t) + N(t))^2 \, dt \quad b_k = 0, 1
\]

\[
x_{jn}^p = \begin{cases} \sqrt{8E_p^p / T_p} \int_0^{T_p} \cos(2\pi f_c t) (J(t) + N(t)) \, dt & b_k = 0 \\ -\sqrt{8E_p^p / T_p} \int_{T_b/2}^{T_p+T_b/2} \cos(2\pi f_c (t-T_b/2)) (J(t) + N(t)) \, dt & b_k = 1 \end{cases}
\]
Analysis of Interference Robustness

**Goal:** OOK/BPPM specific statements on the robustness of energy detection in presence of interference → Processing Gain (PG)

\[
P_G^O = 10 \log_{10} \left( \frac{2E_b^2}{0.5 \cdot Q_1^O + Q_2^O} \right) - 10 \log_{10} \left( \frac{E_b}{T_b (P_j + P_N)} \right), \quad \text{OOK}
\]

\[
P_G^P = 10 \log_{10} \left( \frac{E_b^2}{Q_1^P + Q_2^P} \right) - 10 \log_{10} \left( \frac{E_b}{T_b (P_j + P_N)} \right), \quad \text{BPPM}
\]

where \(Q_1^i\) and \(Q_2^i\), \(i \in \{O, P\}\): second order moments of \(x_{s\text{jn}}^i\) and \(x_{j\text{jn}}^i\), \(i \in \{O, P\}\)

Maximization of PG ⇔ Minimization of \(Q_1^i\) and \(Q_2^i\), \(i \in \{O, P\}\)
According to regulation of ECC: Consideration of an MIR UWB system with four subbands of equal bandwidth $B = 625$ MHz

Analysis focuses solely on the first subband located at $f_c = 6.3125$ GHz

Extension to other subbands or MIR UWB configurations easily possible

System parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration</td>
<td>$T_p = 3.2$ ns</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>$d_s = 0.5 \rightarrow T_b = 6.4$ ns</td>
</tr>
<tr>
<td>Mean transmit power</td>
<td>Normalized to one</td>
</tr>
<tr>
<td>Modulation specific pulse energy</td>
<td>$E_p^i, i \in {O, P}$</td>
</tr>
<tr>
<td>SNR at the input of energy detection</td>
<td>10 dB</td>
</tr>
</tbody>
</table>
PG of OOK/BPPM vs. $\text{SINR}_{\text{in}}$

- **Interference parameters:**

  \[
  T_{b,j} = 102.4 \text{ ns},
  \]
  \[
  f_j = f_c + 50 \text{ MHz},
  \]
  \[
  B_{j,1} = 20 \text{ MHz} \Rightarrow d_j(B_{j,1}) = 0.4883,
  \]
  \[
  B_{j,2} = 400 \text{ MHz} \Rightarrow d_j(B_{j,2}) = 0.0244
  \]
PG of OOK/BPPM vs. $f_J$

- Interference parameters:
  
  $T_{b,J} = 102.4 \text{ ns}$,
  
  $\text{SINR}_{in} = 0 \text{ dB} \rightarrow E_{b,J}(\text{SINR}_{in})$,
  
  $B_{J,1} = 20 \text{ MHz},$
  
  $B_{J,2} = 400 \text{ MHz}$
Interference parameters:

- $T_{b,J} = 102.4$ ns,
- $f_j = f_c + 50$ MHz,
- $\text{SINR}_{\text{in}} = 0$ dB $\Rightarrow E_{b,J}(\text{SINR}_{\text{in}})$,
- $B_{J,1} = 20$ MHz,
- $B_{J,2} = 400$ MHz
Summary

- Investigation of OOK/BPPM based energy detection robustness in presence of noise as well as narrow- and broadband interference

- Based on the energy detector's PG, closed-form expressions of noise and interference related second order moment statistics at the output of an energy detection receiver can be derived using Parseval's theorem as well as the theorem of Price. The results can be verified regarding tone interference

- Analysis of the relative modulation specific PG with respect to various interference parameters shows the robustness of OOK/BPPM based energy detection. Statements on the modulation specific detection performance are possible

- Analysis offers the possibility to optimize the configuration of an arbitrary MIR UWB system with respect to interference
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Assumption: Block transmission fits periodicity of interference

\[ \Rightarrow \text{All interference-free time-frequency slots can be used for data transmission according to a two-dimensional bandplan } L. \]
Coexistence Approaches (1/4)

Otsu-Method

- Image processing: Threshold used to reduce a gray-level image into a binary image
  - Two pixel classes
  - Calculation of optimum threshold to separate those two classes
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- MIR UWB
  - Allocation of energy values to $k$ levels ($1 \leq k \leq L$)
  - Energy classes: $k \leq k_{Otsu} \Rightarrow C_0$: not interfered energy values
    - $k > k_{Otsu} \Rightarrow C_1$: interfered energy values
Coexistence Approaches (1/4)

- **MIR UWB**
  - Allocation of energy values to \(k\) levels (\(1 \leq k \leq L\))
  - Energy classes: \(k \leq k_{\text{Otsu}} \rightarrow C_0: \) not interfered energy values
    \(k > k_{\text{Otsu}} \rightarrow C_1: \) interfered energy values
  - Histogram generation
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  - Energy classes:
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  - Histogram generation
  - Normalization of probability distribution
    - Occurrence probability
      \[ \omega(k) = \sum_{i=1}^{k} p_i \]
Coexistence Approaches (1/4)

- MIR UWB
  - Allocation of energy values to $k$ levels ($1 \leq k \leq L$)
  - Energy classes: $k \leq k_{Otsu} \Rightarrow C_0$: not interfered energy values
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    - Occurrence probability $\omega (k) = \sum_{i=1}^{k} p_i$
    - Mean $\mu (k) = \sum_{i=1}^{k} i \cdot p_i$
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  - Normalization of probability distribution
    - Occurrence probability $\omega(k) = \sum_{i=1}^{k} p_i$
    - Mean $\mu(k) = \sum_{i=1}^{k} i \cdot p_i$
    - Between-class variance as goodness criterion
      $$\sigma^2_b(k) = \frac{(\mu(L) \cdot \omega(k) - \mu(k))^2}{\omega(k) \cdot (1 - \omega(k))}$$

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Coexistence Approaches (1/4)

- **Otsu-Method**
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    - $k > k_{\text{Otsu}} \Rightarrow C_1$: interfered energy values
  - Histogram generation
  - Normalization of probability distribution
    - Occurrence probability
    - Mean
    - Between-class variance as goodness criterion
    - Optimal threshold $k_{\text{Otsu}}$ located at the maximum of $\sigma_b^2(k)$
Coexistence Approaches (2/4)

Coexistence approach 1: Global method
- Transmitter: Blocks of binary zeros
- Receiver: Threshold $k_{Otsu}$ for each block
- Bandplan: Deactivation of detected interfered energy values
Coexistence Approaches (3/4)

Coexistence approach 2: Global iterative method
Coexistence Approaches (4/4)

Coexistence approach 3: Local hierarchical iterative method

- $X_{i,j} > X_{i-1,j}$
- $\max_{i,j} X_{i,j}$
- Coexistence approach 1 in sub-band i, with artificial noise energy values
- $K_{\text{now}} > K_o$?
  - yes: Logging location of detected noise in one cell, modify $\Lambda$
  - no: Deactivation of sub-band i, modify $\Lambda$

Diagram showing iterative process with decision points and conditions.
Results

- **Detection efficiency**
  MB OFDM UWB 1: $\text{SIR}_1 = 0 \, \text{dB}$
  MB OFDM UWB 2: variable $\text{SIR}_2$
  no WLAN

- **BER performance**
  $\text{SIR}_{\text{MB OFDM UWB 1}} = 5 \, \text{dB}$
  $\text{SIR}_{\text{MB OFDM UWB 2}} = 0 \, \text{dB}$
  $\text{SIR}_{\text{WLAN}} = -10 \, \text{dB}$
Summary

- **Adaptive on-line coexistence approaches** based on image processing can handle multiple interference operating with difference interference power
  - Global coexistence approach cannot handle such realistic situations
  → Extension to **global iterative and local hierarchical iterative coexistence** methods
  - Both coexistence approaches outperform the global coexistence approach

- Performance investigations with respect to **reliable detection of multiple interference** and **bit error rate** show the coexistence approaches' contribution to **increased system capacity**

- Coexistence approaches are capable of being **integrated efficiently into the existing MIR UWB architecture** with minor complexity increase
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Teager-Kaiser (TK) Operation (1/2)

- Up to now: Interference robustness of energy detection, Coexistence approaches, (flexible) Detect & Avoid etc.
- Goal: Operation of MIR UWB in presence of (multiple) narrowband interference (NBI)

<table>
<thead>
<tr>
<th>NBI avoidance techniques at the transmitter</th>
<th>NBI suppression techniques at the receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiband schemes, multi-carrier approaches, pulse shaping methods, etc.</td>
<td>Analog notch filtering, digital cancelation via adaptive filtering, etc.</td>
</tr>
</tbody>
</table>

- analog approaches require exact information about NBI
- digital approaches have minor practical meaning for UWB systems

⇒ In the following: Modified energy detector based on TK operation

Teager-Kaiser (TK) Operation (2/2)

- Nonlinear differential operator
- Definition:
  \[ \psi(s(t)) = s(t)^2 - s(t)s(t) \]

- Properties:
  \[ \psi(s_1 + s_2) = \psi(s_1) + \psi(s_2) + \psi_c(s_1, s_2) \]
  \[ \psi(s_1 + s_2 + s_3) = \psi(s_1) + \psi(s_2) + \psi(s_3) + \psi_c(s_1, s_2) + \psi_c(s_1, s_3) + \psi_c(s_2, s_3) \]

where \( \psi_c(s_1, s_2) = 2s_1s_2 - s_1s_2 - s_2s_1 \)

Example:
\[ s(t) = A \cos(\omega t + \theta) \quad \rightarrow \quad \psi(s(t)) = A^2 \omega_c^2 \]

\[ S(\omega_c) \rightarrow 0.5 A \]

\[ \rightarrow \text{DC converter!} \]
One Bandpass Signal (1/2)

- Assumption: N sinusoids of equal amplitude 2A and frequencies $\omega_1 < \ldots \omega_N$ modulated with $\omega_c = (\omega_L + \omega_H)/2 >> 2\omega_N$

$$s_b(t) = \sum_{i=1}^{N} 2A \sin(\omega_i t + \phi_i) \cos(\omega_xt) = \sum_{i=1}^{N} A \left[ \sin((\omega_c + \omega_i)t) \right] + \sum_{i=1}^{N} (-A) \left[ \sin((\omega_c - \omega_i)t) \right]$$

- Approximation of TK output $\psi(s_b(t)) = \psi(s_R(t)) + \psi(s_L(t)) + \psi_c(s_R(t), s_L(t))$

\[
\psi(s_R(t)) \approx K_R + \sum_{i=1}^{N} \sum_{j>i}^{N} 2A^2 \omega_c^2 \cos\left[(\omega_i - \omega_j)t\right], K_R = \sum_{i=1}^{N} A^2 (\omega_c + \omega_i)^2
\]

\[
\psi(s_L(t)) \approx K_L + \sum_{i=1}^{N} \sum_{j>i}^{N} 2A^2 \omega_c^2 \cos\left[(\omega_i - \omega_j)t\right], K_L = \sum_{i=1}^{N} A^2 (\omega_c - \omega_i)^2
\]

\[
\psi_c(s_R(t), s_L(t)) \approx \sum_{i=1}^{N} \sum_{j=1}^{N} (-2A^2 \omega_c^2) \cos\left[(\omega_i + \omega_j)t\right]
\]
One Bandpass Signal (2/2)

- Approximation of TK output

\[
\psi(s_b(t)) \approx K_R + K_L + \sum_{i=1}^{N} \sum_{j>i}^{N} 4A^2 \omega_c^2 \cos \left[ (\omega_i - \omega_j)t \right] - \sum_{i=1}^{N} \sum_{j=i}^{N} 2A^2 \omega_c^2 \cos \left[ (\omega_i + \omega_j)t \right]
\]

- Conclusion:
  - \( \psi(s_b(t)) \) consists of a DC component as well as sinus terms with difference and sum frequencies \( (N,2) \) combinations of \( \omega_1, \ldots, \omega_N \) in which lower frequency terms have more power.
  - Spectrum of \( \psi(s_b(t)) \) spans from 0 to \( 2\omega_N \)
  - Extension to arbitrary center frequencies possible if \( \omega_c >> (\omega_H - \omega_L) \)

NBI bandwidth << center frequency and bandwidth of a MIR UWB subband: Suppression of NBI via highpass filtering (HPF)!
Modified Energy Detection Receiver

\[
\begin{align*}
\text{LNA} & \rightarrow \text{BPF} \rightarrow (.)^2 \rightarrow \triangleright \rightarrow \geq \rho_i \rightarrow H_1 \\
& \rightarrow \leq \rho_i \rightarrow H_0 \\
\end{align*}
\]

„Traditional“ energy detection receiver

\[
\begin{align*}
\text{LNA} & \rightarrow \text{BPF} \rightarrow \text{TK} \rightarrow \text{HPF} \rightarrow (.)^2 \rightarrow \triangleright \rightarrow \geq \rho_i^* \rightarrow H_1 \\
& \rightarrow \leq \rho_i^* \rightarrow H_0 \\
\end{align*}
\]

Modified TK based energy detection receiver
Modified Energy Detection Receiver

... Integration into MIR UWB
Illustration of NBI Mitigation

- Within an MIR UWB subband: Spectrum at three different TK stages (TK input signal, TK output signal, signal after HPF)
- SNR = 11 dB, SIR = - 5 dB,
- Interference source: IEEE 802.11a WLAN $f_c = 5.14$ GHz, $B = 20$ MHz
- Elliptic HPF, $n = 6$, $R_p = 0.1$, $R_s = 50$, 50 MHz
**KBandpass Signals**

- Modeling with $N_k$ sinusoids of amplitude $A_k$ centered with $B_k = 2\omega_{N_k}$ around $\omega_c, (\omega_c \gg 2\omega_{N_k})$

\[
s_{b_k}(t) = \sum_{i=1}^{N_k} A_k \left[ \sin \left( (\omega_{c_k} + \omega_{k,i})t \right) \right] + \sum_{i=1}^{N_k} (-A_k) \left[ \sin \left( (\omega_{c_k} - \omega_{k,i})t \right) \right]
\]

\[
\psi \left( \sum_{k=1}^{K} s_{b_k}(t) \right) = \sum_{k=1}^{K} \left( \psi \left( s_{R_k}(t) \right) + \psi \left( s_{L_k}(t) \right) \right) + \sum_{k=1}^{K} \sum_{l=k+1}^{K} \psi_c \left( s_{R_k}(t), s_{L_l}(t) \right)
\]

\[
+ \sum_{k=1}^{K-1} \sum_{l=k+1}^{K} \left( \psi_c \left( s_{R_k}(t), s_{R_l}(t) \right) + \psi_c \left( s_{L_k}(t), s_{L_l}(t) \right) \right) + \sum_{k=1}^{K} \sum_{l=k}^{K} \psi_c \left( s_{R_k}(t), s_{L_l}(t) \right)
\]

- **Conclusion:**
  - Contributions due to each single NBI source: Spectrum of $k^{th}$ NBI signal ranges from DC to the NBI’s bandwidth
  - Additional cross components according to different NBI sources $k$ and $l$: Spectral components around the difference of absolute center frequencies $|\omega_{c_k} - \omega_{c_l}|$
Verification with Simulations
Broadband Interference Mitigation

- Broadband interference (BBI): a second noncoherent MIR UWB system

- Idea: Segmentation of integration interval $T_i$ in $K$ equal subintervals $T_i$
  
\[
x = \sum_{k=0}^{K-1} x_k = \int_{x_0}^{x_K} [y(t)]^2 \, dt + \int_{(K-1)T_i}^{KT_i} [y(t)]^2 \, dt
\]

- Integration of soft values into decision

\[
\lambda_k = \frac{p_k(x_k \mid 1)}{p(x_k \mid 0)}, \quad k = 0, \ldots, K-1
\]

- Assumption: statistically independent energy values in each subinterval
  
  $\rightarrow$ Mutually independent subdecisions

\[
\prod_{k=0}^{K-1} \lambda_k \geq 1 \rightarrow 1, \prod_{k=0}^{K-1} \lambda_k < 1 \rightarrow 0
\]
Modified Decision Rule (1/2)

- Observation
  - Reduced impact of weak decisions if $|\lambda_k| \approx 1$
  - Increased impact of strong decisions if $|\lambda_k| \ll 1$ or $|\lambda_k| \gg 1$
  - $\lim_{x \to \infty} p(x|0) = 0, \lim_{x \to \infty} p(x|1) = 0$

- Drawback: Likelihood ratio tends to infinity for large energy values
  \[ \lim_{x \to \infty} \frac{p_k(x|1)}{p_k(x|0)} \to \infty \]

$\Rightarrow$ Strong interference within one subinterval may falsify the bit decision!
Modified Decision Rule (2/2)

- Solution: Modification of likelihood ratios

\[
0 < c \ll \max_x \{ p(x | 0), p_0(x | 1), \ldots, p_{K-1}(x | 1) \}
\]

\[
\lambda_k = \frac{p_k(x_k | 1) + c}{p(x_k | 0) + c}, \quad k = 0, \ldots, K-1
\]

\[
\prod_{k=0}^{K-1} \lambda_k \geq 1 \rightarrow 1, \quad \prod_{k=0}^{K-1} \lambda_k < 1 \rightarrow 0
\]

- Advantage: \( \lim_{x \to \infty} \frac{p_k(x | 1) + c}{p(x | 0) + c} \to 1 \)

\[\Rightarrow\] Large energy values resulting from strong interference can be suppressed
Result

- BER vs. SIR, $E_b/N_0 = 13$ dB with/without interference mitigation
- MIR UWB subband of $300$ MHz width, $T_b = 40$ ns
- Interference: a 2nd asynchronous MIR UWB system with $T_b = 1.33$ ms
- 1 subinterval ($T_i = 25$ ns) and 5 subintervals ($T_i = 5$ ns) for $c = 0$, $c = 0.1$ and $c = 0.001$
Summary

- Crucial issue within MIR UWB: Mitigation of interference passing the analog front-end

- Analytical and simulative analysis of a TK based energy detection receiver to mitigate NBI
  - TK + HPF promises the mitigation of one NBI signal without any a priori information on its frequency location at very low additional cost
  - In case of multiple NBI additional cross components occur which might degrade detection performance

- Analytical and simulative study to mitigate non cooperative BBI
  - Usage of subintervals → Multi dimensional ML detection
  - Strong interference within one subinterval may falsify the bit decision
  - Modified likelihood ratio can reduce the influence of BBI

- NBI and BBI mitigation is capable of being integrated into the existing MIR UWB architecture with minor complexity increase
Interference investigations within noncoherent multiband impulse radio UWB

Thank you!