Submission Title: [IG DEP Space-time domain interference mitigation using based on OMF and TDL-AA for dependable UWB-BANs]

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Re: []

Abstract: [As a dependable PHY technology for wireless body area network (WBAN), schemes of Space-time domain interference mitigation using based on OMF and TDL-Array Antenna are introduced.]

Purpose: [information]

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Space-Time Domain Interference Mitigation Using OMF and TDL-AA for Dependable UWB Wireless Body Area Networks (UWB-WBANs)

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†CWC, University of Oulu (CWC UofOulu)
**Issues on multiple BAN environment**

**Inter-user interference**
- IR-UWB uses the same pulse as all users signal in the same standard.
- Other users signal and/or the other network signal would be interference.

**Inter-system interference**
- Interference from the other wireless system using overlapped frequency band. ⇒ Unknown

* 802.11a (wi-fi) (5GHz) overlaps

User A wants to connect to “B”.

UWB-WBAN IEEE 802.15.6

Other UWB system. e.g. IEEE 802.15.4a

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**Purpose and Suggestion**

- **Sparate** and **Recognize** each interference from different source. ⇒ Apply suitable interference mitigation method according to source of interference.

- Using both of Spatial and Temporal signal processing.

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**Inter-user** interference

“IUI” in this presentation

Interference from a system using the same pulse

**Inter-system** interference

“ISI” in this presentation

Interference from a system using overlapped frequency

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**Known**

Recognize and demodulate

*Pulse shape multiple access Multi-user detection*

**Unknown**

Remove

*Interference canceller*
Matched Filter (MF) 1

Matched Filter (MF) 2

Matched Filter (MF) 3

Matched Filter (MF) k

Antenna

Desired signal + interference

Orthogonal

Orthogonal

Orthogonal

Orthogonal

Linear combiner

Matched Filter (MF) 1

Matched Filter (MF) 2

Matched Filter (MF) 3

Matched Filter (MF) k

Desired signal + interference

+ Replica of interferences

- subtract

W1

W2

W3

Wk

Adaptive algorithm e.g., LMS

Mixed signal EXCEPT desired signal.
OMF; orthogonal matched filter

- consists a matched filter \((MF_1)\) and MF Group \((MFG)\)
- Tap coefficients of \(MF_1\) are the same as sequence of desired signal.
- Coefficients of \(MF_1\) and each \(MF_k\) that constituting MFG are orthogonal.
- Desired signal does not through \(MF_{2\sim K-1}\) because orthogonality. →only interference can through.
- MFG makes replica of interference signal by linear combination with weight vector \(w\) of linear combiner; LC.
- Subtract interference replica from the output of \(MF_1\).

**OMF can remove interference without any pre-knowledge of interference.**
• Modified Hermite pulse; MHP applied to IR-UWB communication (Mohammad Ghavami et al.)

- Pulse function generated by modified Hermitian polynomials.
- Pulses are **orthogonal** each other in sync. \((t=0)\) condition.
- Cross correlation =0. \(\Rightarrow\) no interference
- In async. \((t\neq 0)\) condition, not orthogonal.

\[
h_n = \exp\left(-\frac{(t / t_p)^2}{4}\right) \frac{d^n}{dt^n} \left(\exp\left(-\frac{(t / t_p)^2}{2}\right)\right)
\]
Orthogonality of MHP

- MHP: Modified Hermite Pulse
- Each user uses unique order MHP as its transmission signal.
- \( n \)-th order MHP is generated by \( n \)-th order modified Hermite polynomial.
- In sync. \((t=0)\) and no distortion condition, MHPs are **orthogonal**.
  (cross correlation = 0)
- Channel propagation makes it distortion. \(\Rightarrow\) NOT orthogonal.

Interference canceller

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• Proposed OMF with Multi-user detection

◆ As MF and MFG of OMF,
  • Use discrete sampled MHP.
  • Gramm-Schmidt orthonormalization is used for fill deficit in MFG.

◆ By utilizing the MHP as a MFG…
  • Known user’s signal which uses same MHP as MFG can be retrieved.
  • Unknown interference can be cancelled

\[ r(n) \]

- MUD

\[ \sum_n (\cdot) \]

- ISI mitigation

Proposed system for 2 users detection.

**MUD and ISI mitigation**

Works at the same time
• System model and theoretical analysis.

**Rx signal**

\[ r(n) = \sum_{u=1}^{U} a_u(n) b_u g_u, \]

In vector form

\[ \mathbf{a}_u = [a_u(1), a_u(2), \cdots, a_u(N)]^T, \]
\[ \mathbf{c}_k = [c_k(1), c_k(2), \cdots, c_k(N)]^T, \]
\[ \mathbf{r} = [r(1), r(2), \cdots, r(N)]^T. \]

\( \mathbf{c}_k \) is the \( k \)-th orthogonal vector

\( \mathbf{a}_1 = \mathbf{c}_1 \) is desired user’s pulse

\[ \mathbf{MF}_k \ (k = 1, 2) \] output included in \( \mathbf{LC}_k \)

\[ \mathbf{w}_k^T \mathbf{r} = \mathbf{w}_k^T \sum_{u=1}^{U} \mathbf{a}_u^T \mathbf{c}_k b_u g_u. \]
- System model and theoretical analysis

Desired signal is assumed as $a_1$

$$\mathbf{c}_1 = a_1^T a_1 b_1 g_1 + \sum_{u=2}^{U} a_u^T a_1 b_u g_u$$

$$= b_1 g_1 + \sum_{u=2}^{U} b_u g_u a_u^T a_1,$$

Desired signal included in $\text{LC}_1$

$$\sum_{k=2}^{K} \mathbf{c}_k^T \mathbf{w}_k = \sum_{u=2}^{U} b_u g_u \sum_{k=2}^{K} \mathbf{w}_k^T \mathbf{c}_k^T \mathbf{a}_u.$$

Interference is cancelled in condition satisfies...

$$\sum_{u=2}^{U} b_u g_u a_u^T a_1 + \sum_{u=2}^{U} b_u g_u \sum_{k=2}^{K} \mathbf{w}_k^T \mathbf{c}_k^T \mathbf{a}_u = 0,$$

$$\Rightarrow a_u^T a_1 = - \sum_{k=2}^{K} \mathbf{w}_k^T \mathbf{c}_k^T \mathbf{a}_u.$$
System model and theoretical analysis

Interference is cancelled in condition satisfies:

$$\sum_{u=2}^{U} b_u g_u a_u^T a_1 + \sum_{u=2}^{U} b_u g_u \sum_{k=2}^{K} w_k^1 c_k^T a_u = 0,$$

$$\Rightarrow a_u^T a_1 = - \sum_{k=2}^{K} w_k^1 c_k^T a_u.$$

In matrix:

$$\begin{pmatrix} a_2^T a_1 \\ \vdots \\ a_U^T a_1 \end{pmatrix} = - \begin{pmatrix} a_2^T c_2 & \ldots & a_2^T c_K \\ \vdots & \ddots & \vdots \\ a_U^T c_2 & \ldots & a_U^T c_K \end{pmatrix} \begin{pmatrix} w_2^1 \\ \vdots \\ w_K^1 \end{pmatrix} = -B \begin{pmatrix} w_2^1 \\ \vdots \\ w_K^1 \end{pmatrix}.$$

Optimum weight vector

*without noise

$$w_{opt}^1 = -B^{-1} A.$$
• Numerical evaluation

• Assumed MHP-UWB which uses MHP as transmission pulse.
• Each user uses unique order MHP as a transmission pulse.
  → Adaptive algorithm estimates an optimum solution by using this known preamble.
• IUI and ISI exist.

(a) IEEE 802.15.6 UWB PHY frame format.

(b) Simplified frame structure supposed in this paper.

SHR    PHR    PSDU
contains MAC frame with data and FCS etc.

PHR: physical layer header    PSDU: Physical layer service data unit
MUD and ISI canceller – Numerical evaluation.

**Scenario 1**
- **Unknown system (DS-UWB)**
- **Target System (MHP-UWB)**

<table>
<thead>
<tr>
<th>DIR [dB]</th>
<th>-40 to +40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known user</td>
<td>2 (0(^{th}) and 3(^{rd}) MHP)</td>
</tr>
<tr>
<td>Unknown interference</td>
<td>Gold sequence DS-UWB, 29 users</td>
</tr>
<tr>
<td>Channel (dist. / noise)</td>
<td>IEEE 802.15.6 CM3 path loss model + AWGN</td>
</tr>
<tr>
<td>Iteration for LMS / NLMS</td>
<td>2,000 ~ 32,000 / 4,000 ~ 64,000</td>
</tr>
</tbody>
</table>

**Scenario 2**
- **Target System (MHP-UWB)**

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Slide 14
Results of SC.1

Square error (SC.1).

$L_{1}/N_{0} = +60$dB, $DIR=0$dB

LMS & NLMS algorithm towards minimum square error.

Multiple user’s signal retrieved with interference reduction.

Weight coefficients (SC.1) $E_{b}/N_{0} = +60$dB, $DIR=0$dB.

Adaptive algorithm makes approx. solution.

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Slide 15
Results (noise free channel)

**DIR vs. BER (SC.1)** \( E_b/N_0 = +\infty \text{dB} \).

**DIR vs. BER (SC.2)** \( E_b/N_0 = +\infty \text{dB} \).

More iteration number makes higher capacity of interference reduction.

Takumi Kobayashi (YNU), Ryuji Kohno (YNU/CWC)
UofOulu
Simulation results (noise free channel)

DIR vs. BER $E_b/N_0 = +\infty$ dB.

More iteration number makes higher capacity of interference reduction.

Takumi Kobayashi (YNU), Ryuji Kohno (YNU/CWC UofOulu)

Slide 17
Simulation results (noise & interference channel)

$W_{opt}$ which is generated by theory does not satisfy minimum error in high DIR condition. $\Rightarrow W_{opt}$ is not optimal solution in environment in which noise exists.

High DIR $\Rightarrow$ dominant cause of bit error is noise

$\text{DIR vs. BER (SC.2) } E_b/N_0 = +25\text{dB.}$
Results of SC.1

Square error characteristics in various DIR (SC.1).

Adaptive algorithm does not find an optimum weights in low DIR and low $E_b/N_0$. ⇒ ⇒ ⇒ Theoretical analysis with Noise

Square error characteristics in various DIR (SC.1). $E_b/N_0=+120$ dB, DIR=-40dB ~ +40dB

$E_b/N_0=+25$ dB, DIR=-40dB ~ +40dB

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Theoretical analysis

Analyse a theoretical solution which satisfies MMSE criteria

\[ E_{\text{mul}}^2 = a_1^T n + \sum_{k=2}^{K} \sum_{u=2}^{U} c_k^T a_u b_u g_u \{ -w_{opt,k}^T (1-\Delta) \} + \sum_{k=2}^{K} c_k^T n w_{opt,k} + \sum_{k=2}^{K} c_k^T n \{ -w_{opt,k}^T (1-\Delta) \} \]

Size reduction of weight vector by a coefficient \( \Delta \)

\[ w' = \Delta w_{opt} \]

Residual interference

- When \( W \neq W_{opt} \), interference remains.

\[ \Rightarrow \text{residual interference is increased} \]

\[ \Rightarrow \text{noise enhancement is suppressed} \]

Adaptive algorithm try to find MMSE “as smaller as possible” \( \Rightarrow \) not optimum

\[ \Delta \text{ becomes smaller} \]
Smaller Δ makes

⇒ residual interference is increased
⇒ noise enhancement is suppressed

optimum solution = \( \Delta_{opt} \mathbf{w}_{opt} \)

\[ \Delta_{opt} = \arg \min_{0 \leq \Delta \leq 1} f(\Delta) \]

\[ f(\Delta) = \frac{E_{\text{mul}}^2}{\sigma_{\text{in}}^2 \| \mathbf{w} \|^2} + \sum_{u=2}^{U} \left( \tilde{a}_1^T \tilde{a}_u \right)^2 G_I^2 \]

\( \Delta_{opt} \) depends on power of interference and noise

Adaptive algorithm cannot find \( \Delta_{opt} \) but it can find approximate solution.

\[ \Delta_{opt} = \frac{\sum_{u=2}^{U} \left( \tilde{a}_1^T \tilde{a}_u \right)^2 G_I^2}{\sigma_{\text{in}}^2 \| \mathbf{w} \|^2} \]

\[ \Rightarrow \text{residual interference is increased} \]
\[ \Rightarrow \text{noise enhancement is suppressed} \]

\( \mathbf{w}' = \Delta \mathbf{w}_{opt} \)

\( \mathbf{w}_{opt} \) is shrunk by \( \Delta \leq 1 \).

Δ which satisfies MMSE in various DIR (SC.2)

\[ E_b/N_0 = +25 \text{dB} \]
Theoretical performance

Smaller $\Delta$

⇒ residual interference is increased
⇒ noise enhancement is suppressed

Larger $\Delta$

⇒ residual interference is suppressed
⇒ noise enhancement is increased

Optimum solution

optimum solution = $\Delta_{opt} w_{opt}$
$\Delta_{opt}$ value in each $Eb/N0$ and DIR conditions

Optimal solution $\Delta_{opt} w_{opt}$ provides a performance limit of our proposing system.

Although our system cannot remove noise, MSE can be reduced in low noise situation.

In High DIR and Low Eb/N0 channel, $\Delta_{opt}$ becomes close to 0 (zero).

In Low DIR and High Eb/N0 channel, $\Delta_{opt}$ becomes close to 1 (one).
Space-time domain interference mitigation using TDL array antenna for MHP based IR-UWB

4.1 Proposed system model and theoretical analysis

4.2 Numerical evaluation and results
TDL-AA ; Tapped delay line array antenna

- Array antenna by using multiple antenna elements and tapped delay line.
- Each antenna branch has coefficients.
- Transfer function of this antenna has parameters of signal incoming angle; $\theta$ and frequency; $\omega$.

$\Rightarrow$ has characteristics of both of spatial and time domain.

$\tau_n = \frac{d}{c} \sin \theta$,

$y(t) = \exp(j\omega t) \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \exp(-j\omega(\tau_n + mT_0))w_{n,m}$,

$= \exp(j\omega t) \times H(\theta, \omega)$,

$H(\theta, \omega) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} w_{n,m} \exp(-jm\omega T_0) \exp(-j\omega \frac{d}{c} \sin \theta)$.

**TDL-AA can work as interference canceller on both of time and space domains**
• Apply pulse based OMF to spatial signal processing

**TDL array antenna**

• Configured by multiple antennas and tapped delay line (TDL)

• TDL-AA can separate the signals which comes from the same direction by using time-domain signal processing.

**By applying OMF to TDL-AA**

• Interference reduction is performed on the both of domains of time and space.
• System model and optimum parameters.

**Beam forming,**
- Delay time of each antenna branch is adjusted to achieve Maximum Power of desired signal

\[
\delta_n = \left( n - \frac{N - 1}{2} \right) \frac{d_s}{\nu} \sin(\theta_0)
\]

- \( N \): number of antennas,
- \( \nu \): propagation speed
- \( d_s \): antenna distance

**Null-steering,**
- MHP based OMF is used as a TDL.
- arrival time difference of \( u \)-th users signal in \( n \)-th antenna is

\[
\tau_{u,n} = -\left( n - \frac{N - 1}{2} \right) \frac{d_s}{\nu} \sin(\theta_u)
\]
• System model

- Delay time for beam forming is

\[ \delta_n = -\tau_{0,n} \]

- OMF of \( n \)-th brunch has coefficients \( c_n(t) \) that satisfy bellow

\[
c_n(t) = a_0 + \sum_{k=1}^{K-1} p_k(t)w_k
\]

where, \( w_k \) is determined as

\[
a_0(t)^T a_u(t + \tau_{u,n} + \delta_n) = -\sum_{k=1}^{K-1} a_u(t + \tau_{u,n} + \delta_n)^T p_k(t)w_{k,n} \quad (u = 1, 2, \ldots, U - 1)
\]

\[
\begin{bmatrix}
w_{0,n} \\
\vdots \\
w_{K-1,n}
\end{bmatrix} = 
\begin{bmatrix}
a_1(t + \tau_{1,n} + \delta_n)^T p_1(t) & \cdots & a_1(t + \tau_{1,n} + \delta_n)^T p_{K-1}(t) \\
\vdots & \ddots & \vdots \\
a_{U-1}(t + \tau_{U-1,n} + \delta_n)^T p_1(t) & \cdots & a_{U-1}(t + \tau_{U-1,n} + \delta_n)^T p_{K-1}(t)
\end{bmatrix}^{-1}
\begin{bmatrix}
a_0(t)^T a_1(t + \tau_{1,n} + \delta_n) \\
\vdots \\
a_0(t)^T a_{U-1}(t + \tau_{U-1,n} + \delta_n)
\end{bmatrix}
\]

\[ a_0 = p_0 \] is desired user’s pulse \( a_u \) is \( u \)-th user’s pulse (undesired) \( p_k \) \( k \)-th orthogonal vector
Characteristics evaluation on each arrival angle

**Scenario 6**

- **Unknown system (Chirped pulse UWB)**
- **Target System (MHP-UWB)**

- Number of antennas / placement: 5 / Linear array
- Distance between antennas; $d_s$ [m]: 0.45
- Desired user’s pulse: 0th order MHP
- Interference user’s pulse: 2nd order MHP (IUI) and chirped pulse UWB (ISI)
- Arrival angle of desired signal [degree]: 10
- Arrival angle of interference signal [degree]: 30 and -60

**Scenario 7**

- Unknown system (Chirped pulse UWB)
- Target System (MHP-UWB)
- Arrival angle of interference signal [degree]: 0 and 0
**System has gain against an interference → residual interference**

**TDL-AA without null-steering (SC.6)**

**Gain ≠ 0**

**Space-temporal interference reduction (SC.7)**

**Interference signal is reduced**

Gain ≠ 0
**TDL-AA without null-steering**  \((SC.6)\)

System has gain against an interference →residual interference

**Space-temporal interference reduction** \((SC.7)\)

Interference signal is reduced
Characteristics evaluation on each arrival angle

2 users use the same pulse

**Time-domain signal processing cannot reduce the interference**

<table>
<thead>
<tr>
<th>Scenario 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 users use the same pulse</td>
</tr>
</tbody>
</table>

Using same pulse

<table>
<thead>
<tr>
<th>Characteristics evaluation on each arrival angle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of antennas / placement</strong></td>
</tr>
<tr>
<td><strong>Distance between antennas;</strong> $d_s$ [m]</td>
</tr>
<tr>
<td><strong>Desired user’s pulse</strong></td>
</tr>
<tr>
<td><strong>Arrival angle of desired signal [degree]</strong></td>
</tr>
<tr>
<td><strong>Interference user’s pulse</strong></td>
</tr>
<tr>
<td><strong>Arrival angle of interference signal [degree]</strong></td>
</tr>
</tbody>
</table>
System has gain against an interference $\rightarrow$ residual interference

**TDL-AA without null-steering with OMF**

\[ \text{Gain} \neq 0 \]

Interference can be eliminated if either one is different from the desired signal

**Space-temporal interference reduction (SC.8)**
Enhanced OMF Extended to Circular Array Antenna

[Suzuki, 2015]
Enhanced OMF Extended to Circular Array Antenna
Application to V2V communication

Desired user

Undesired users

January 2021

Takumi Kobayashi (YNU), Ryuji Kohno (YNU/CWC UofOulu)
8 users

30 users
Extended orthogonal matched filter into space-time domains for cancelling interference in inter-vehicle communication and radar
ITS · IVC

ITS : Intelligent Transport System

✓ ETC
✓ VICS (Vehicle Information and Communication System)
✓ Collision avoidance radar
✓ Autonomous driving

IVC : Inter-Vehicle Communication
- Wireless communication between vehicle to vehicle
- By sharing position, speed, controlling information, IVC supports safety driving
- Should be Realtime and Dependable
DS/CDMA: Direct-Sequence Code Division Multiple Access

- 3G Cellular etc. …
- Each user uses different DS-code
- Spread spectrum
- CDMA is basing on code orthogonality

**Cellular system**
- Base station
- Transmission power control
- Pre-known user code
  ⇒ interference cancelling

**IVC (ad-hoc network)**
- No base-station
- Vehicle mobility
- No transmission control
- Unknown user code

Near-far problem System (user) capability

V2V Comm.

- Spread spectrum
- CDMA is basing on code orthogonality

- Direct-Sequence Code Division Multiple Access

- 3G Cellular etc. …
- Each user uses different DS-code
- Spread spectrum
- CDMA is basing on code orthogonality
Adaptive array antenna

① RF signal is received multiple antennas.
② Linear combination by weighting vector.
③ Desired signal and interference signal separated spatially.
  Beamforming
  Null steering

Interference canceller in
Space domain
Serial combination of OMF and AAA

1. SIR improvement by AAA in spatial domain
2. Interference canceller by OMF in time domain

AAA and OMF work as interference canceller complementary.
Extended Space-Time domain OMF

- Filtering for both of desired signal and interference in space-time domain.
- Convergence performance improvement.
## Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK</td>
</tr>
<tr>
<td>Spread spectrum</td>
<td>DSSS</td>
</tr>
<tr>
<td>Code</td>
<td>31bit Gold-sequence</td>
</tr>
<tr>
<td>Tx power</td>
<td>10[mW]</td>
</tr>
<tr>
<td>Center freq.</td>
<td>760[MHz]</td>
</tr>
<tr>
<td>Antenna</td>
<td>5 elements circular array</td>
</tr>
<tr>
<td>Channel</td>
<td>AWGN (-103.8[dBm])</td>
</tr>
<tr>
<td>User number</td>
<td>4</td>
</tr>
<tr>
<td>Data size</td>
<td>1000[bit]</td>
</tr>
<tr>
<td>Arrival angle</td>
<td>Desired signal: 0 deg. Interference ±180 deg. or ±10deg</td>
</tr>
</tbody>
</table>

![Diagram of vehicles with labels: Own vehicle, Desired vehicle, Interference vehicle](image_url)
BER-DIR performance

5 users, (1 desired user, 4 interference)

BER performance is improved in high DIR situation.
BER-DIR performance

30 users, (1 desired user, 29 interference)

Extended OMF can improve BER performance.
Conclusion

- OMF based on Modified Hermite pulse have been proposed.
  - Interference reduction against unknown interference.
  - Multi user detection for known pulse users signal.

=> Interference mitigation (reduction) in Time-domain.

- MHP based OMF is combined with TDL-AA.
  - Interference mitigation on Time and space domains signal processing.

=> Space-time domain interference mitigation.
References (1/2)


Thank you for your attention.