Study of coexistence between UWB and narrowband cellular systems

Bruxelles, 09. December 2003

Chair for Communications Theory
Communications Laboratory
Dresden University of Technology

Christian Müller, Martin Mittelbach
Outline

- Problem
- Problem Analysis
- Model of Scenario
  - Physical Model
  - Statistical Model
  - Combination of Models
- Solution Issues
- Simulation Results
- Conclusions
I. Problem
Problem

- **Objective:**
  - Investigate the impact of cumulative interference from multiple UWB systems to a narrowband victim receiver.

- **Object of investigation:**
  - Cellular victim receiver (downlink)
  - Indoor environment
  - 3D UWB device distribution
  - Traffic model for UWB devices

- **Result:**
  - Statistical model for aggregate UWB interference

- **Main question:**
  - What is the maximum acceptable UWB device density?
II. Problem Analysis
Problem Analysis

- Promising approach in:

  “UWB aggregate interference on a cellular victim receiver from a statistical perspective“  


- Main assumptions of approach:
  - 2D geometrical model
  - Ring rearrangement
  - Traffic model
  - Only first two rings considered as presenting dominant contribution
    - Exact calculation for first two rings
    - Gaussian approximation for interference PDF of external rings

1) Christian Müller, Martin Mittelbach
Dresden
University of Technology

Bruxelles, 09. December 2003
Problem Analysis

Promising approach in:

“UWB aggregate interference on a cellular victim receiver from a statistical perspective” ¹

Main assumptions of approach:

- 2D geometrical model
- Ring rearrangement
- Traffic model
- Only first two rings considered as presenting dominant contribution
  - Exact calculation for first two rings
  - Gaussian approximation for interference
    PDF of external rings

Problem Analysis

Total interference:

\[ I = I_{1+2} + I_\infty = \sum_{i=1}^{2} N_i P_i + \sum_{i=3}^{\infty} N_i P_i \]

Histogram of UWB interference \( I_\infty \) (rho=0.5)

Histogram of UWB interference \( I_\infty \) (rho=5.0)

Compare: \( I_{1+2} = 4.814 \)

Compare: \( I_{1+2} = 60.444 \)
Problem Analysis

Objective: Keep model as general as possible

Main differences in our approach:
- No change in the rectangular grid to keep uniform device distribution
- No general assumptions about contribution of external devices
- No assumptions about interference PDF of external devices
- Extension to 3D

Steps to solve the problem:
- Characteristics specification (victim receiver, UWB device, environment, …)
- Model development (physical model, statistical model, …)
- Choosing solving method (analytical, simulation, …)
III. Model of Scenario
Model of Scenario

What is the objective target of the scenario model?
- Derive a multiple UWB device model including a traffic approach.
- Derive a relation to measure the UWB to narrowband system interference.
- Provide a base for investigations, i.e. analysis and simulations.

How to achieve the scenario model?
- Task 1: Derive a physical model (system char.).
- Task 2: Derive a statistical Model (traffic).
- Task 3: Combine physical and statistical model.

What other specific points should we take respect to?
- The scenario model is not unique.
- There are a number of points that need discussion.
III. Model of Scenario

Task 1: Physical Model
Physical Model

What components does the physical model depend on?

- Characteristics of:
  - Environment *(free-space reference distance, path loss, …)*.
  - Victim receiver *(center frequency, bandwidth, …)*.
  - UWB interferer *(power spectral density, number of devices, …)*.
  - Geometry *(dimension, device distribution)*.

How to achieve the physical model?

- **Step 1:** derive single UWB device interference
- **Step 2:** derive multiple UWB device interference
- **Step 3:** derive victim receiver degradation
Physical Model – Step 1

- Environment characteristics:
  - $r$ := victim receiver – UWB distance
  - $d_0$ := free-space reference distance
  - $n$ := path loss exponent

- Victim receiver characteristics:
  - $B_{VR}$ := bandwidth of victim receiver
  - $\lambda$ := wavelength ($c / f_c$)

- UWB interferer characteristics:
  - $G_p$ := power spectral density

$$P_r = \begin{cases} 
  P_0 \left(\frac{d_0}{r}\right)^2 & \text{if } r \leq d_0 \\
  P_0 \left(\frac{d_0}{r}\right)^n & \text{if } r > d_0 
\end{cases}$$

$$P_0 = \frac{G_p B_{VR} \lambda^2}{(4\pi d_0)^2}$$
Physical Model – Step 1

- Get emission limits for UWB communication systems from FCC/ETSI mask.

- Note, *we assumed a modified FCC* mask with change to -75 dBm/MHz for frequencies below 960 MHz *(this point needs discussion).*

![Diagram showing UWB emission limits for indoor systems](image.png)
## Physical Model – Step 1

### Summary of parameters for Physical Model – Step 1: single UWB device interference

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Parameter</th>
<th>Symbol</th>
<th>GSM-900</th>
<th>GSM-1800</th>
<th>UMTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>victim receiver</td>
<td>lambda [m]</td>
<td>$\lambda$</td>
<td>0.333</td>
<td>0.167</td>
<td>0.140</td>
</tr>
<tr>
<td></td>
<td>bandwidth [MHz]</td>
<td>$B_{VR}$</td>
<td>0.2</td>
<td>0.2</td>
<td>5.0</td>
</tr>
<tr>
<td>UWB device</td>
<td>power spectral density [dBm/MHz]</td>
<td>$G_p$ -FCC</td>
<td>-75</td>
<td>-53.3</td>
<td>-51.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_p$ -ETSI</td>
<td>-98</td>
<td>-72.0</td>
<td>-65.3</td>
</tr>
<tr>
<td>environment</td>
<td>free-space distance [m]</td>
<td>$d_0$</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>path loss exponent</td>
<td>$n$</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2) frequency band 2.11 – 2.17 GHz assumed


4) NLOS, see also: U.C.A.N coexistence study - presentation, UWB cluster meeting, Sept. 2003
Physical Model – Step 2

Definition of 3D model

- $R_0$ := UWB – UWB distance
- $\rho$ := UWB device density ([1/m³])

$$R_0 = 1/\sqrt[3]{\rho}$$

- $\tilde{r}$ := victim receiver – UWB distance

$$\tilde{r} = \frac{R_0}{2} \sqrt{(2i-1)^2 + (2j-1)^2 + (2k-1)^2}$$

- $\tilde{I}_{UWB}$ := UWB interference to victim receiver

$$\tilde{I}_{UWB} = \sum_{\tilde{r}} P_{\tilde{r}} = P_0 \left[ \sum_{\tilde{r} \leq d_0} \left( \frac{d_0}{\tilde{r}} \right)^2 + \sum_{\tilde{r} > d_0} \left( \frac{d_0}{\tilde{r}} \right)^n \right]$$
Normalized 3D model

- \( r \) := distance UWB – UWB distance

\[
r = \sqrt{(2i - 1)^2 + (2j - 1)^2 + (2k - 1)^2}
\]

- \( r_0 \) := free-space reference distance

\[
r_0 = 2d_0 \sqrt[3]{r \rho}
\]

- \( I_{UWB} \) := UWB interference to victim receiver

\[
I_{UWB} = \sum_r P_r = P_0 \left[ \sum_{r \leq r_0} \left( \frac{r_0}{r} \right)^2 + \sum_{r > r_0} \left( \frac{r_0}{r} \right)^n \right]
\]

- \( I_0 \) := normalized UWB interference to victim receiver

\[
I_0 = I_{UWB} / P_0
\]
Physical Model – Step 3

Definition of link budget degradation due to UWB\(^5\) (needs to be discussed):

\[
M_{UWB}[dB] = 10\log_{10}\left(\frac{I_{co} + N_0 + \hat{I}_{UWB}}{I_{co} + N_0}\right)
\]

Maximum acceptable UWB interference:

\[
\hat{I}_{UWB} = (I_{co} + N_0) \cdot \left(10^{M_{UWB}[dB]/10} - 1\right)
\]

We have to compare:

\[
I_{UWB} \leq \hat{I}_{UWB}
\]

specified by UWB characteristics + regulation

specified by victim receiver characteristics

\(^5\) similar to definitions in: U.C.A.N coexistence study - presentation, UWB cluster meeting, Sept. 2003

and: SwissCom: Study of Interference effects of a UWB mass deployment on GSM systems., 2003
Physical Model – Step 3

Victim receiver noise and co-channel interference:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GSM-900</td>
</tr>
<tr>
<td>thermal noise [dBm]</td>
<td>(N_{th})</td>
<td>-121.0(^7)</td>
</tr>
<tr>
<td>receiver noise [dBm]</td>
<td>(N_0)</td>
<td>-112.0(^7)</td>
</tr>
<tr>
<td>co-channel interference [dBm]</td>
<td>(I_{co})</td>
<td>-102.8(^7)</td>
</tr>
</tbody>
</table>

Maximum acceptable UWB interference

<table>
<thead>
<tr>
<th>(M_{UWB} [dB])</th>
<th>(\hat{I}_{UWB} [dBm])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GSM-900</td>
</tr>
<tr>
<td>1(^9)</td>
<td>-108.2</td>
</tr>
<tr>
<td>3(^9)</td>
<td>-102.4</td>
</tr>
</tbody>
</table>

\(^6\) UMTS voice service assumed

\(^7\) details on parameters and calculation in coexistence deliverable [D5.4b]

\(^8\) value taken from: Radiocommunications Agency: *Impact of UWB on Third-Generation Telecommunications*, 2003

\(^9\) taken from: Ericsson: *Generic power spectral density limits for a single UWB interferer*, 2002
In subsequent model normalized interference is considered:\(^{10}\)

\[ \hat{I}_0 = \frac{\hat{I}_{UWB}}{P_0} \]

<table>
<thead>
<tr>
<th>Mask</th>
<th>$M_{UWB}$ [dB]</th>
<th>GSM-900</th>
<th>GSM-1800</th>
<th>UMTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_0$ [dBm]</td>
<td>$\hat{I}_0$</td>
<td>$P_0$ [dBm]</td>
<td>$\hat{I}_0$</td>
</tr>
<tr>
<td>FCC</td>
<td>1</td>
<td>-113.5</td>
<td>3.408</td>
<td>-97.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>13.100</td>
<td></td>
</tr>
<tr>
<td>ETSI</td>
<td>1</td>
<td>-136.5</td>
<td>679.981</td>
<td>-116.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>2613.723</td>
<td></td>
</tr>
</tbody>
</table>

\(^{10}\) $d_0 = 1\text{m}$ assumed
III. Model of Scenario

Task 2: Statistical Model
Statistical Model

What communication traffic do we assume?

- We assume devices are switched on at a certain probability $p$. This value is called the activity factor.

| activity factor [%] | $p$ | 5, 2.5, 111 |

- We assume independent device activity.

How can we derive a suitable statistical model?

1. **Step 1:** single UWB device probability distribution
2. **Step 2:** multiple UWB device probability distribution

11) typical values as e.g. in: SwissCom: Study of Interference effects of a UWB mass deployment on GSM systems., 2003
Statistical Model – Step 1

What is an appropriate statistical model for a single UWB device?

We define a basic space $\Omega_i$ with two events for the $i$-th UWB device:

$$\Omega_i = \{A, A^C\} \quad \text{where} \quad \begin{cases} A \ldots, \text{device is switched on} \\ A^C \ldots, \text{device is switched off} \end{cases}$$

We set the probability for any event possible:

$$P(A) = p \quad \text{and} \quad P(A^C) = (1 - p)$$

We define a random variable $X_i$ for the $i$-th UWB device:

$$X_i(\omega) = a_i \cdot 1_A(\omega) \quad , \omega \in \Omega_i, 1_A \text{ indicator}$$

We derive the probability distribution for $X_i$:

$$P(\{X_i(\omega)\}) = P(\{\omega : X_i(\omega) \in \{0, a_i\}\}) = \begin{cases} P(A) & \text{if} \quad X_i(\omega) = a_i \\ P(A^C) & \text{if} \quad X_i(\omega) = 0 \end{cases} , \omega \in \Omega_i$$
How can we extend the statistical model for multiple UWB devices?

Since we assumed independent device activity, we may apply the statistical product approach.

We derive the product space $\Omega$ for $m$ UWB devices:

$$\Omega = \Omega_1 \times \ldots \times \Omega_m = \{\omega = (\omega_1, \ldots, \omega_m): \omega_i \in \{A, A^c\}, i = 1, \ldots, m\}$$

We define the random variable $S_m$ for $m$ UWB devices:

$$S_m(\omega) = X_1(\omega_1) + \ldots + X_m(\omega_m) = \sum_{i=1}^{m} X_i(\omega_i), \omega = (\omega_1, \ldots, \omega_m) \in \Omega$$

We derive the probability distribution for $S_m$:

$$P(\{S_m(\omega)\}) = P(\{\omega: S_m(\omega) \in R\}) \quad , \omega \in \Omega$$
III. Model of Scenario

Task 3: Combination of Models
Combination of Models

What have we achieved so far?

- An expression of the normalised UWB interference for an infinite number of devices without traffic. (Physical Model)
- A value for the maximum acceptable UWB interference. (Physical Model)
- A random variable and its probability function modelling the traffic. (Statistical Model)

How can we combine both models?

Step 1:
combine normalised interference and traffic

Step 2:
derive a value for the maximum degradation
Combine Models – Step 1

- Combine the normalised interference $I_0$ with the random variable $S_m$.
  - The normalized interference without traffic. All UWB devices are switched on. (Physical Model)
    \[
    I_0 = \frac{1}{P_0} \sum_r P_r = \frac{1}{P_0} \sum_{r_i} P_{r_i}
    \]
  - The random variable models the traffic. A maximum number of $m$ UWB devices are switched on. (Statistical Model)
    \[
    S_m(\omega) = \sum_{i=1}^m X_i = \sum_{i=1}^m a_i I_A(\omega_i) , \omega = (\omega_1, \ldots, \omega_m) \in \Omega
    \]
  - The combined expression provides a normalised interference $I_{0,m}$ for $m$ UWB devices including the traffic.
    \[
    I_{0,m}(\omega) = \sum_{r_i} \frac{P_{r_i}}{P_0} I_A(\omega_i) = \sum_{i=1}^m \left( \frac{r_0}{r_i} \right)^2 I_A(\omega_i) + \sum_{i=1}^m \left( \frac{r_0}{r_i} \right)^n I_A(\omega_i) , \omega = (\omega_1, \ldots, \omega_m) \in \Omega
    \]
Combine Models – Step 2

Combine the comparison of interference levels with the statistical approach to derive a probability that the degradation is larger than a permitted level.

Comparison of the actual and the maximum acceptable interference level. (Physical Model)

\[ x \leq M_{UWB} \iff I_{UWB} \leq \hat{I}_{UWB} \iff I_0 \leq \hat{I}_0 , \quad x \in [0, \infty) \]

Introducing statistics gives the probability we are looking for. In multiple publications this is called the outage probability.

\[ P(M_{UWB}(\omega) \geq x) = P(I_0(\omega) \geq \hat{I}_0) = P(\{\omega: I_0(\omega) \geq \hat{I}_0\}) , \quad \omega \in \Omega , \quad x \in [0, \infty) \]

There is one point to take care on. If we only respect to a finite number of \( m \) devices, then we only have the following inequality.

\[ P(I_{0,m}(\omega) \geq \hat{I}_0) \leq P(I_0(\omega) \geq \hat{I}_0) , \quad \omega \in \Omega \]
IV. Solution Issues
Solution Issues

What have we achieved up to this point in time?

Our major question is: What UWB device density is permitted to not exceed the acceptable link budget degradation at a certain probability?

We derived a scenario model that takes respect to:

- A multiple UWB device environment.
- A rectangular 3D geometry.
- A statistical model for the communication traffic.

What approaches might be suitable to answer our question?

Find a probability density function matching the parameter sets to calculate the outage probability.

Step 1: try analytical approach

Step 2: apply Monte-Carlo simulation
In the first approach, an analytical solution has been pursued.

Conjecture:

\[ F_{I_{0,m}}(x) \xrightarrow{m \to \infty} N(\mu, \sigma^2) \]

where

\[ F_{I_{0,m}}(x) = P(I_{0,m} \leq x) \]

By applying the Lindeberg's theorem we could prove that this conjecture is not valid.

Detailed investigations showed:

- In general, it is very difficult to find a probability distribution function because of the strong dependence on the variety of parameters.
Solution Issues – Step 2

How to simulate the scenario model applying the Monte-Carlo approach?

Assume the 3D grid from above and choose its maximum radius $r_{\text{max}}$. The grid then includes $N_d$ devices.

For any single device get the radius $r_i \leq r_{\text{max}}$ and calculate:

- If $(r_i < r_0)$ then $a_i := (r_0 / r_i)^2$; else $a_i := (r_0 / r_i)^n$;

For a number of $N$ random experiments repeat:

- Generate a number of $N_d$ uniformly distributed numbers $x_i$ of $(0,1)$.
- Apply the indicator function, i.e.
  - If $(x_i \leq p)$ then $I_A(\omega_i) := 1$; else $I_A(\omega_i) := 0$;
- Calculate an interference value $I_{0,m} := \Sigma a_i I_A(\omega_i)$ with $m := N_d$.
- From the $N$ interference values $I_{0,m}$ calculate the outage probability.
- For graphical presentation generate histograms of the $N$ interference values $I_{0,m}$.
V. Simulation Results
Simulation Results

Relative frequency of UWB interference ($d_0 = 1\text{m}, n = 4, N_d = 25576, N = 1\text{e6}$)
Simulation Results

Outage probability\(^{12)}\) applying FCC mask  

Outage probability\(^{12)}\) applying ETSI mask

<table>
<thead>
<tr>
<th>$\rho$ [1/m(^3)]</th>
<th>$P(\text{MUWB} \geq 1 \text{ dB}) \leq 1%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p = 0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>p = 0.025</td>
<td>0.06</td>
</tr>
<tr>
<td>p = 0.01</td>
<td>0.08</td>
</tr>
</tbody>
</table>

\(^{12)}\) GSM-1800, $d_0 = 1m$, $n = 4$, $N_d = 25576$, $N = 1e6$
Simulation Results

Permitted UWB device density\(^{13}\) for \(P(M_{\text{UWB}} \geq x\text{dB}) \leq 1\%\)

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Mask} & M_{\text{UWB}} [\text{dB}] & p [\%] & \text{device density rho} [1/\text{m}^3] \\
\hline
\multicolumn{4}{|c|}{\text{GSM-900}} & \text{GSM-1800} & \text{UMTS} \\
\hline
\text{FCC} & 5.0 & 1.019 & 0.056 & 0.008 \\
& 2.5 & 1.302 & 0.062 & 0.009 \\
& 1.0 & 2.802 & 0.101 & 0.014 \\
\hline
3 & 5.0 & 4.838 & 0.146 & 0.021 \\
& 2.5 & 7.811 & 0.165 & 0.024 \\
& 1.0 & 15.458 & 0.276 & 0.037 \\
\hline
\text{ETSI} & 5.0 & 484.829 & 2.314 & 0.086 \\
& 2.5 & 928.431 & 3.329 & 0.095 \\
& 1.0 & 2215.112 & 6.773 & 0.152 \\
\hline
3 & 5.0 & 2312.874 & 10.911 & 0.232 \\
& 2.5 & 4775.758 & 18.647 & 0.262 \\
& 1.0 & 13066.434 & 38.067 & 0.421 \\
\hline
\end{array}
\]

\(^{13}\) \(d_0 = 1\text{m}, n = 4, N_d = 25576, N = 1e5\)
Simulation Results

Minimum distance\(^{14)}\) between nearest UWB interferer and victim receiver for 
\[ P(M_{UWB} \geq x dB) \leq 1\% \]

<table>
<thead>
<tr>
<th>Mask</th>
<th>(M_{UWB}) [dB]</th>
<th>(p) [%]</th>
<th>minimum distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>GSM-900</td>
</tr>
<tr>
<td>FCC</td>
<td>1</td>
<td>5.0</td>
<td>0.860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>0.793</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>0.614</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.0</td>
<td>0.512</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>0.436</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>0.348</td>
</tr>
<tr>
<td>ETSI</td>
<td>1</td>
<td>5.0</td>
<td>0.110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>0.089</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>0.066</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.0</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>0.037</td>
</tr>
</tbody>
</table>

\(^{14)}d_0 = 1m, n = 4, N_d = 25576, N = 1e5
Conclusions

- Maximum UWB device densities could be derived based on FCC / ETSI regulation applying statistical simulations.

- Protection efficiency of FCC / ETSI indoor mask at an outage probability of 1%:
  - **FCC mask:**
    - GSM 900: sufficient protection
    - GSM 1800: insufficient protection if $M_{UWB} = 1\text{dB}$ required
    - GSM 1800: sufficient protection if $M_{UWB} = 3\text{dB}$ required
    - UMTS voice service at 2.14 GHz: insufficient protection
  - **ETSI mask:**
    - GSM 900: very conservative, too protective
    - GSM 1800: sufficient protection
    - UMTS voice service at 2.14 GHz: insufficient protection if $M_{UWB} = 1\text{dB}$ required
    - UMTS voice service at 2.14 GHz: sufficient protection if $M_{UWB} = 3\text{dB}$ required