IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	**UWB Channel Model for under 1 GHz**
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Re:	Adjunct to TG4a channel model document.
Abstract	This paper presents a channel model for UWB pulse systems operating at frequencies below 1 GHz.
Purpose	The purpose of this document is to provide IEEE P802.15 with a 100 MHz-1 GHz channel model for evaluating location aware wireless systems.
Notice	
Release	

UWB Channel Model Components for use below 1 GHz
- Kai Siwiak

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The 100 MHz channel model comprises two components. The first is a LOS in-room component that captures the major reflection sources at low frequencies, which are the walls and floor for the LOS case. The second is a N-LOS component which is based on the Jakes [Jakes 1974] model with exponential energy density profile (EDP). The multipath UWB pulses and impulses are exponentially distributed, their arrival interval is randomly distributed in windows of duration Ts.

For both cases a signal S(t) contains all of the multipath components, weighted by the receiver antenna aperture, and by the receiver antenna efficiency. The method of signal detection, signal convolution the receiver filter, multiplication by the receiver template, and the signal processing will determine which and how many and how efficiently the multipath components are utilized.

The LOS Model

LOS: attenuation is free space intergal over PSD: $d<(RoomX^2+RoomY^2)^{1/2}$ m

- Ricean with Γ^2 power additional from single reflection multipath; Γ^4 form corner reflections
- Multipath is derived from 9 primary reflections of a room model:
  - 4 principal reflections from the walls
  - 1 ground reflection
  - 4 principal corner reflections
- Multiple realizations are utilized.

The following parameters specific the UWB radio performance in a room-LOS condition:
(1) Room dimensions RoomX and RoomY, and minimum distance to a wall dt
(2) Antenna heights h1 and h2
(2) Radiated power spectral density EIRPsd(f)
(3) Receiver antenna aperture Ae
(4) Multipath signal profile S(t)
(5) Average reflection coefficient Γm

Derived parameters include:
- RMS delay spread τrms,
- the mean ray arrival rate Ts
- excess energy factor in the room is Wx

Total energy is accounted for in the room. The "excess" energy in the room should be balanced by the average wall-transmitted energy.

The geometry for the LOS in-room model is shown in Figure 1.

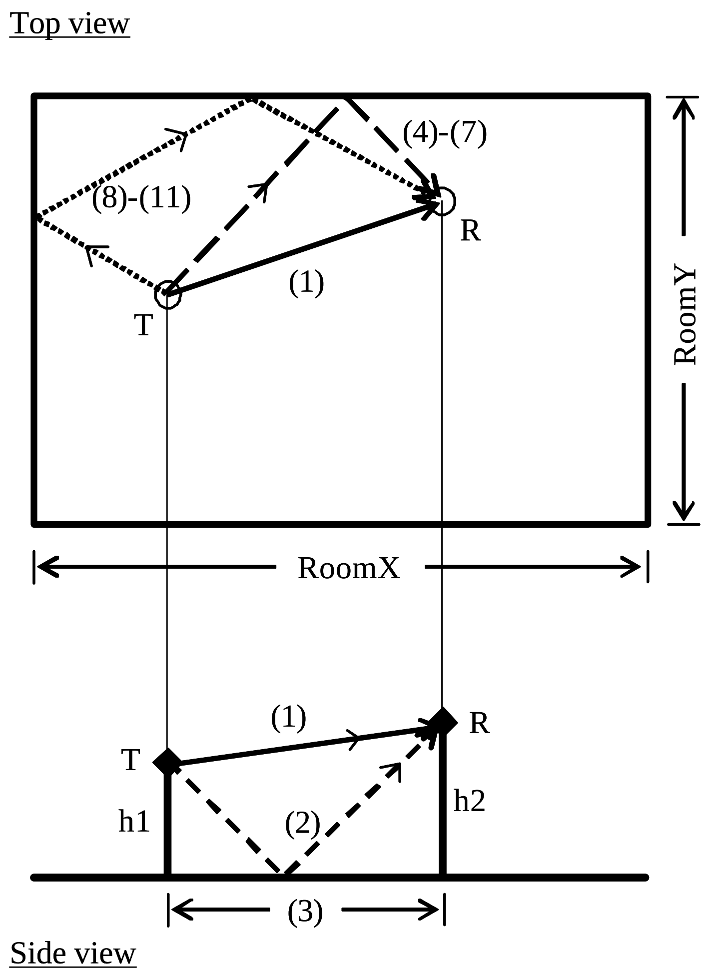

Figure 1. Top and side views of signal paths inside a room.

Reflections are shown for only one wall and for one corner. All four wall and corners are considered in the model.

Non-Line of Sight Multipath Model

The Jakes [Jakes 1974] model with exponential EDP will be applied, here for UWB pulses in non-line of sight (NLOS) cases. Thus the multipath impulses are exponentially distributed, their arrival interval is randomly distributed in windows of duration Ts. The delay spread parameter is a function of distance, [Siwiak 2003] and [Cassiolli 2002], and here is modeled by the square root of distance, see slide 34 of [IEEE802 04/504]. This naturally results in a 2.5 power law in propagation as a function of distance.

The following parameters specific the UWB radio performance in a N-LOS condition:

(1) RMS delay spread parameter $\tau 0$ s/m$^{0.5}$
(2) Mean interval between rays Tm s
(3) Fraction of energy in direct ray K
(4) Radiated power spectral density EIRPsd(f)
(5) Receiver antenna aperture Ae
(6) Multipath signal profile SN(t)

For both channel model components, the signal SN(t) contains all of the multipath components, weighted by the receiver antenna aperture, and by the receiver antenna efficiency. The method of signal detection, signal convolution the receiver filter, multiplication by the receiver template, and the signal processing will determine which and how many and how efficiently the multipath components are utilized.

<u>References</u>:

[Honch 1992] W. Honcherenko, H. L. Bertoni, "Mechanisms governing UHF propagation on single floors in modern office buildings," IEEE Transactions on Vehicular Technology, Vol. 41, No. 4, November 1992, pp. 496-504.

[Jakes 1974] W. C. Jakes. Microwave Mobile Communications, American Telephone and Telegraph Co., 1974, reprinted: IEEE Press, Piscataway, NJ, 1993.

[Cassiolli 2002] D. Cassioli, Moe Z. Win and Andreas F. Molisch, “The Ultra-Wide Bandwidth Indoor Channel: from Statistical Model to Simulations”, IEEE Journal on Selected Areas on Commun., Vol. 20, pp. 1247-1257, August 2002.

[Siwiak 2003] K. Siwiak, H. Bertoni, and S. Yano, “On the relation between multipath and wave propagation attenuation,” Electronic Letters, 9th January 2003, Volume 39 Number 1, pp. 142-143.

[IEEE802 02/249] “Channel Modeling Sub-committee Report – Final,” IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), IEEE document P802.15-02/249r0-SG3a, Dec, 2002. (Online): http://grouper.ieee.org/groups/802/15/pub/2002/Nov02/

[IEEE802 04/504] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), IEEE document P802.15-04/504r1-TG3a, Sept, 2004, 15-04-0504-01-003a-ds-uwb-no-response-eq-sop.ppt

Constants: speed of propagation, m/s $c := 299792458$ $\mu := 4\cdot\pi\cdot 10^{-7}$

$MHz := 10^{6}$ $nanosec := 10^{-9}$

Room dimensions for LOS case, m $RoomX := 3.7$ $RoomY := 4.6$

Minimum distance from walls, m $dt := 0.1$

Antenna heights above the floor, m $h1 := 1.0$ $h2 := 2$

A room in an office or industrial area is modeled as 4 walls with dimensions RoomX and RoomY (m). The radio devices are at heights h1 and h2, and are at least distance dt from any wall. The reflection coefficient Γ is a single average value derived from [Honch 1992].

A direct path and ground reflected path between two radios in the same room is first selected randomly. Then the four principle wall reflections are considered.

The direct and ground reflected path are found from:

$$d(x1,x2,y1,y2) := \sqrt{(x2-x1)^2+(y2-y1)^2+(h2-h1)^2} \quad (1)$$

$$gnd(x1,x2,y1,y2) := \sqrt{(x2-x1)^2+(y2-y1)^2+(h2+h1)^2} \quad (2)$$

Separation distance projected on the ground is

$$dg(x1,x2,y1,y2) := \sqrt{(x2-x1)^2+(y2-y1)^2} \quad (3)$$

The principal reflected paths are the specular images of the direct path.

$$r1(x1,x2,y1,y2) := \sqrt{(x2-x1)^2+(y2+y1)^2+(h2-h1)^2} \quad (4)$$

$$r2(x1,x2,y1,y2) := \sqrt{(x2-x1)^2+(2\cdot RoomY-y2-y1)^2+(h2-h1)^2} \quad (5)$$

$$r3(x1,x2,y1,y2) := \sqrt{(x2+x1)^2+(y2-y1)^2+(h2-h1)^2} \quad (6)$$

$$r4(x1,x2,y1,y2) := \sqrt{(2\cdot RoomX-x2-x1)^2+(y2-y1)^2+(h2-h1)^2} \quad (7)$$

Corner bank reflection paths - two wall reflections - there are two possibilities for projecting each corner image, but both result in the same path distance:

$$c1(x1,x2,y1,y2) := \sqrt{(x2+x1)^2+(y2+y1)^2+(h2-h1)^2} \quad (8)$$

$$c2(x1,x2,y1,y2) := \sqrt{(x2+x1-2\cdot RoomX)^2+(y2+y1)^2+(h2-h1)^2} \quad (9)$$

$$c3(x1,x2,y1,y2) := \sqrt{(x2+x1-2\cdot RoomX)^2+(y2+y1-2\cdot RoomY)^2+(h2-h1)^2} \quad (10)$$

$$c4(x1,x2,y1,y2) := \sqrt{(x2+x1)^2+(y2+y1-2\cdot RoomY)^2+(h2-h1)^2} \quad (11)$$

Equations (1)-(11) are exercised to compute a statistically significant number of randomly selected paths in the room, and the specular reflected paths are also computed. Nrnd is the counter limit for index i and is set to several thousands to get statistically valid results. Coordinates ($XR1_i$, $YR1_i$) and ($XR2_i$, $YR2_i$) of the two direct path endpoints are selected.

Number of trials is: $Nrnd := 10000$ $\quad i := 0 .. Nrnd$

$$X1r_i := rnd(RoomX - 2\cdot dt) + dt \qquad Y1r_i := rnd(RoomY - 2\cdot dt) + dt$$
$$X2r_i := rnd(RoomX - 2\cdot dt) + dt \qquad Y2r_i := rnd(RoomY - 2\cdot dt) + dt \qquad (12)$$

Then the direct D_i distances and ground reflected Gr distances are computed, and the principle specular wall reflection distances $R1_i$, $R2_i$, $R3_i$, $R4_i$ are computed. Corner reflection C1, C2, C3, C4 are found. The path lengths in excess of the direct path are $eR1_i$, $eR2_i$, $eR3_i$, and $eR4_i$; and eC1, eC2, eC3, eC4.

$$D_i := d\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad Dg_i := dg\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right)$$
$$R1_i := r1\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eR1_i := R1_i - D_i$$
$$R2_i := r2\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eR2_i := R2_i - D_i$$
$$R3_i := r3\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eR3_i := R3_i - D_i$$
$$R4_i := r4\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eR4_i := R4_i - D_i$$
$$Gr_i := gnd\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eG_i := Gr_i - D_i \qquad (13)$$
$$C1_i := c1\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eC1_i := C1_i - D_i$$
$$C2_i := c2\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eC2_i := C2_i - D_i$$
$$C3_i := c3\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eC3_i := C3_i - D_i$$
$$C4_i := c4\left(X1r_i, X2r_i, Y1r_i, Y2r_i\right) \qquad eC4_i := C4_i - D_i$$

View a subset of points: $x := 0..300$

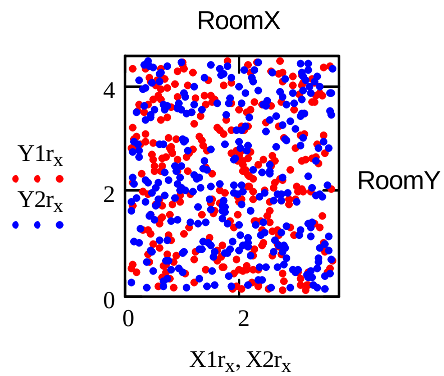

Figure 2. A sampling of the total points (X1, Y1) and (X2, Y2).

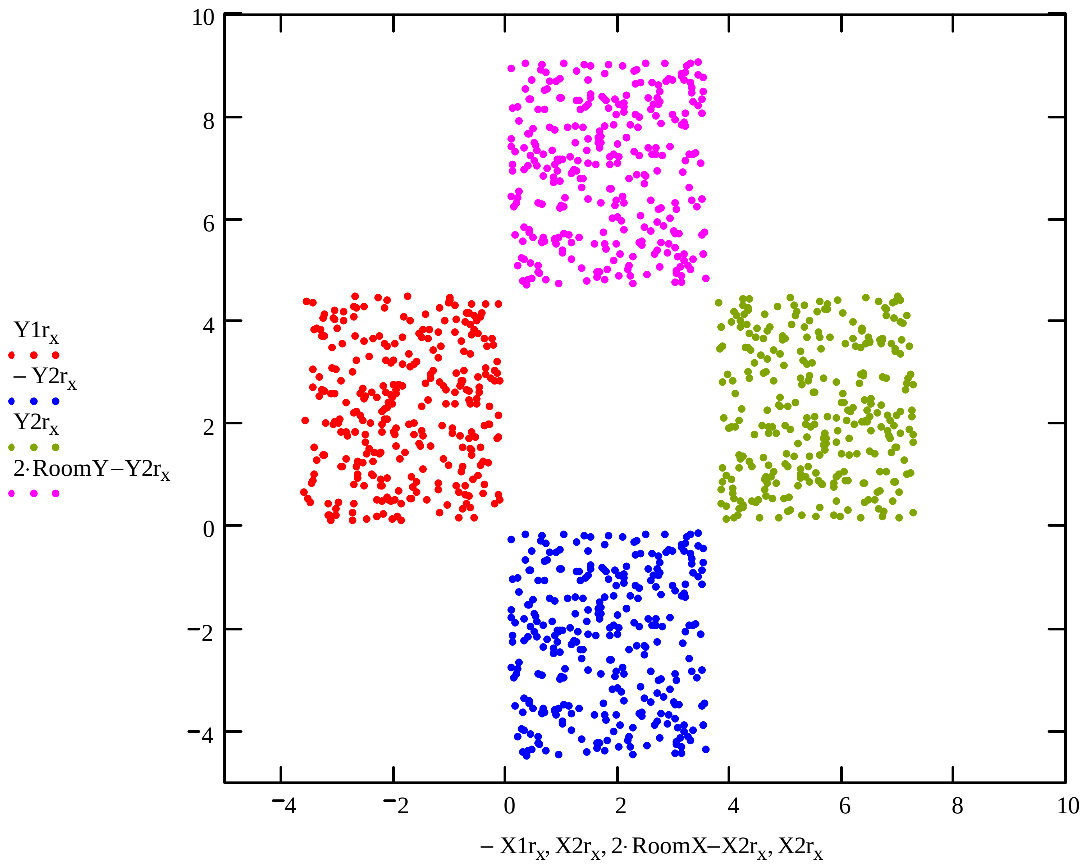

Figure 3. Images in the room walls of the reflection points. C1 are lower left and C2 are lower right, C3 are upper right and C4 are upper left.

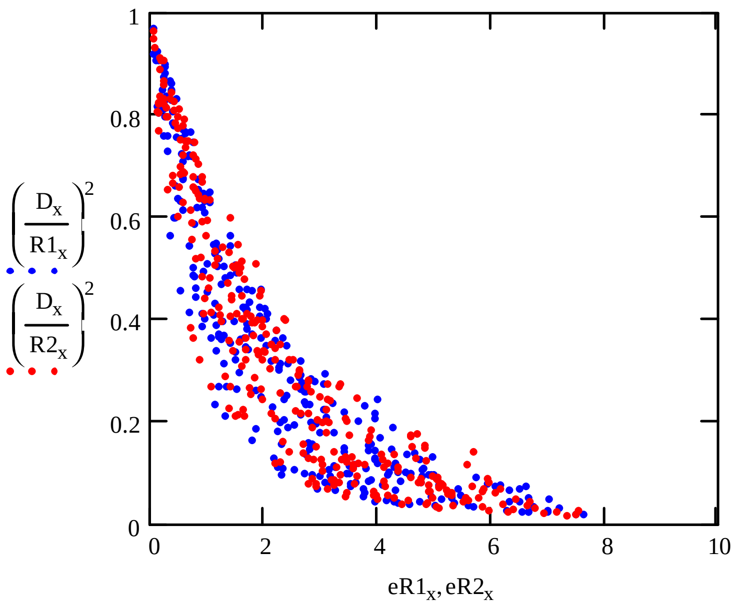

Figure 4. Energy delay profile (EDP) vs. excess delay: R1, R2. The excess delays is associated with the Y dimension of the room.

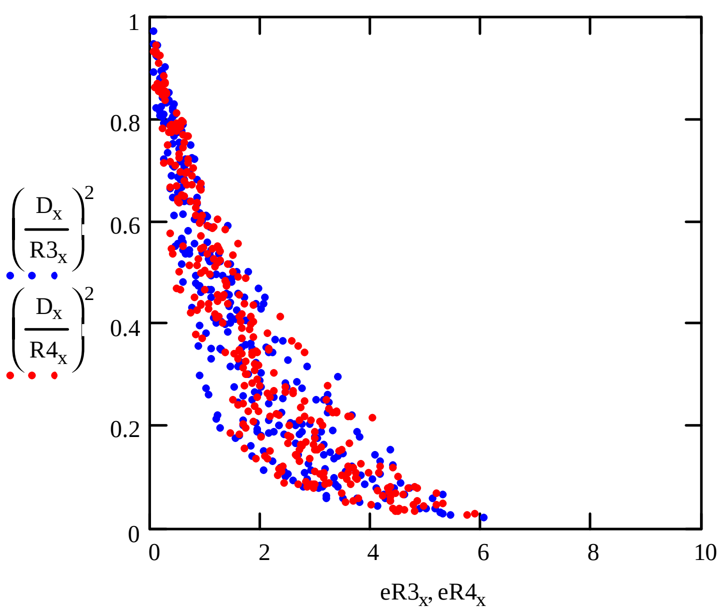

Figure 5. Energy delay profile vs. excess delay, R3, R4. The excess delays are associated with the X dimension of the room.

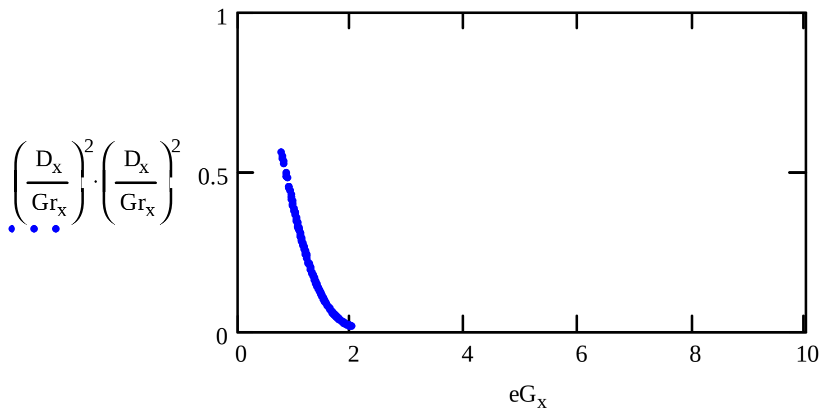

Figure 6. Energy delay profile vs. excess delay, for the ground reflection Gr.

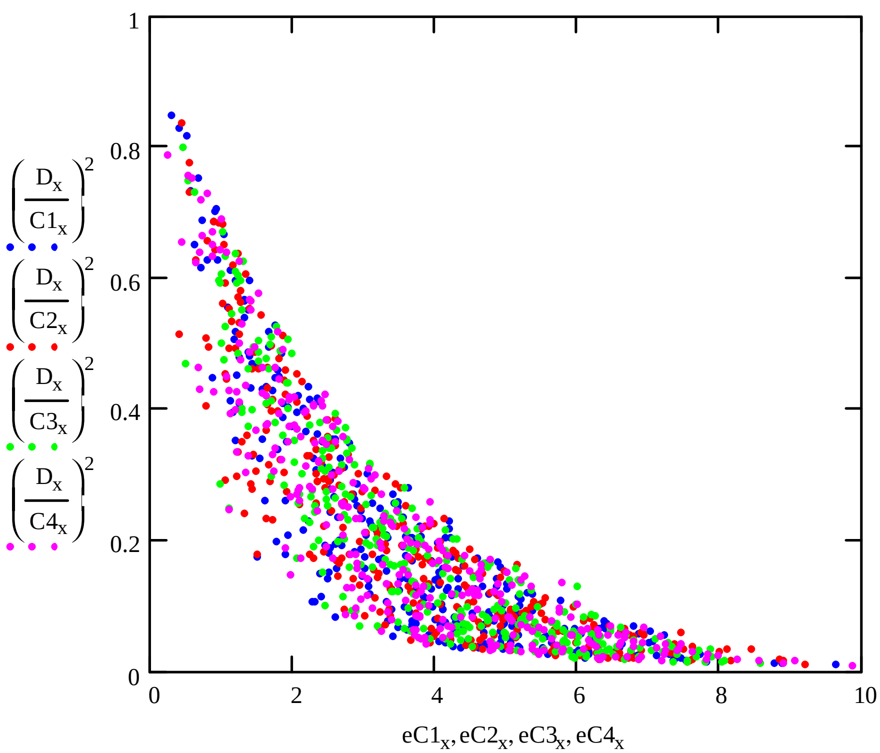

Figure 7. Energy delay profile vs. excess delay, for the corner reflections.

Reflections from the floor and walls.

Reflection coefficient from concrete or plasterboard is between 0.3 for 0 deg, 1 for grazing angle of incidence, see [Honch 1992].

$j := 0..9$

$\Gamma_j :=$	$\Gamma_j =$	$j =$
0.3	0.3	0
0.3	0.3	1
0.3	0.3	2
0.3	0.3	3
$0.3 + \frac{0.7}{5}$	0.44	4
$0.3 + 2 \cdot \frac{.7}{5}$	0.58	5
$0.3 + 3 \cdot \frac{.7}{5}$	0.72	6
$0.3 + 4 \cdot \frac{.7}{5}$	0.86	7
1	1	8
1	1	9

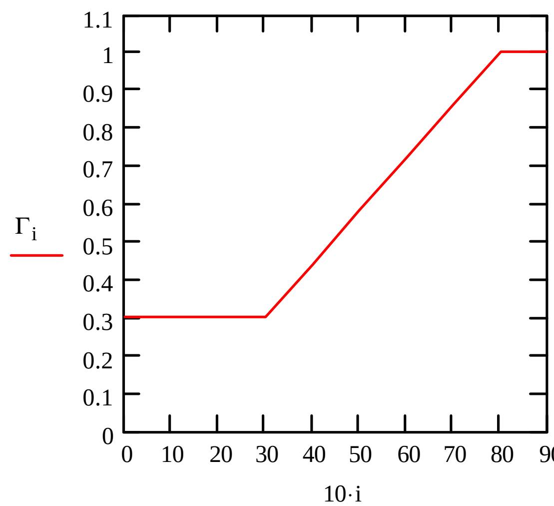

Figure 8. Reflection coefficient vs. incident angle for concrete and plaster board walls. [Honch 1992].

$$\Gamma m := -\text{mean}(\Gamma) \qquad \Gamma m = -0.58 \tag{14}$$

$$20 \cdot \log(|\Gamma m|) = -4.731$$

Considering transmissions through walls, the incidence angle is approximately bounded between normal incidence and about 45 deg.

Normal incidence transmission $20 \cdot \log(1 - .3) = -3.098$

Average incidence transmission $Tm := 1 + \Gamma m$ $20 \cdot \log(Tm) = -7.535$

Secondary reflections involve a transmission and one wall interface followed by a reflection from the back side of the wall followed by the reflection from the front side of the wall. The secondary reflection are thus on the average down by:

$$\Gamma_{2m} := \frac{1}{9} \cdot \sum_{j=0}^{9} \left[\Gamma_j \cdot \left(1 - \Gamma_j\right) \cdot \Gamma_j + .001 \right] \tag{15}$$

$\Gamma_{2m} = 0.084$ $20 \cdot \log\left(\Gamma_{2m}\right) = -21.464$ dB

The average secondary reflection is more than 20 dB attenuated and will be ignored.

Three distinct groupings of the EDP (energy delay profile) are evident in Figures 4-7. These occur because there are three distinct mechanisms in operation. the room is a rectangle so reflections associated with the width and length will cluster differently. Also the ground reflection depends only on separation distance and on antenna heights h1 and h2.

The rms delay spread τrms is the second central moment of the power delay profile for each of path. The energies relative to a direct path are the square of the distance ratio: $(D/R)^2$. The ground reflected component is out of the plane of the other components, and its energy is additionally weighted by the the projection of the vertical field vector on the receive antenna, via the ground reflection hence the ground component relative energy is approximately $(1/Gr)^2(D/Gr)4$. The delay spread is found from

$$tm_i := \left[\left(\frac{D_i}{R1_i}\right)^2\cdot eR1_i + \left(\frac{D_i}{R2_i}\right)^2\cdot eR2_i + \left(\frac{D_i}{R3_i}\right)^2\cdot eR3_i + \left(\frac{D_i}{R4_i}\right)^2\cdot eR4_i + \left(\frac{Dg_i}{Gr_i}\right)^2\cdot\left(\frac{D_i}{Gr_i}\right)^4\cdot eG_i\right]\cdot\Gamma m^2 \;... \\ + \left[\left(\frac{D_i}{C1_i}\right)^2\cdot eC1_i + \left(\frac{D_i}{C2_i}\right)^2\cdot eC2_i + \left(\frac{D_i}{C3_i}\right)^2\cdot eC3_i + \left(\frac{D_i}{C4_i}\right)^2\cdot eC4_i\right]\cdot\Gamma m^4 \tag{16}$$

$$tm2_i := \left[\left(\frac{D_i}{R1_i}\right)^2\cdot\left(eR1_i\right)^2 + \left(\frac{D_i}{R2_i}\right)^2\cdot\left(eR2_i\right)^2 + \left(\frac{D_i}{R3_i}\right)^2\cdot\left(eR3_i\right)^2 \;... \\ + \left(\frac{D_i}{R4_i}\right)^2\cdot\left(eR4_i\right)^2 + \left(\frac{Dg_i}{Gr_i}\right)^2\cdot\left(\frac{D_i}{Gr_i}\right)^4\cdot\left(eG_i\right)^2\right]\cdot\Gamma m^2 \;... \\ + \left[\left(\frac{D_i}{C1_i}\right)^2\cdot\left(eC1_i\right)^2 + \left(\frac{D_i}{C2_i}\right)^2\cdot\left(eC2_i\right)^2 + \left(\frac{D_i}{C3_i}\right)^2\cdot\left(eC3_i\right)^2 + \left(\frac{D_i}{C4_i}\right)^2\cdot\left(eC4_i\right)^2\right]\cdot\Gamma m^4 \tag{17}$$

$$W_i := \left[\left(\frac{D_i}{R1_i}\right)^2 + \left(\frac{D_i}{R2_i}\right)^2 + \left(\frac{D_i}{R3_i}\right)^2 + \left(\frac{D_i}{R4_i}\right)^2 + \left(\frac{Dg_i}{Gr_i}\right)^2\cdot\left(\frac{D_i}{Gr_i}\right)^4\right]\cdot\Gamma m^2 \;... \\ + \left[\left(\frac{D_i}{C1_i}\right)^2 + \left(\frac{D_i}{C2_i}\right)^2 + \left(\frac{D_i}{C3_i}\right)^2 + \left(\frac{D_i}{C4_i}\right)^2\right]\cdot\Gamma m^4 \tag{18}$$

The "total" energy in the room is Wx times the direct path energy: $Wx := mean(W) + 1 \qquad 10\cdot\log(Wx) = 2.05$ dB

$$\tau 2rms_i := \sqrt{\frac{tm2_i}{W_i} - \left(\frac{tm_i}{W_i}\right)^2} \qquad trms := mean(\tau 2rms) \tag{19}$$

$\max(\tau 2rms) = 1.741$ $\min(\tau 2rms) = 0.199$ $trms = 1.201$ meters

Finally the rms delay spread τrms is found

$$\tau rms := \frac{trms}{c} \tag{20}$$

and its value for the selected case is

$$\tau rms \cdot 10^{9} = 4.006 \text{ nS} \qquad \frac{\max(\tau 2rms)}{c} \cdot 10^{9} = 5.808 \text{ nS}$$

Figure 5 shows the EDPs vs. excess delays for all three sets of of reflections. Note the ground reflections (magenta) follow a narrow range of possibilities. An exponential EDP with delay spread τrms is shown as the black trace, but it does not model the room reflections very well. Since the room primary reflections are entirely deterministic, these will be used as the model. The clear areas hugging the abscissa and the ordinate result from setting the two antenna heights to different values.

$scale := 0.2$

$uu := 0..50$ $p := 2$ $f_{uu} := \exp\left(\frac{-uu \cdot scale}{trms \cdot 2}\right)$

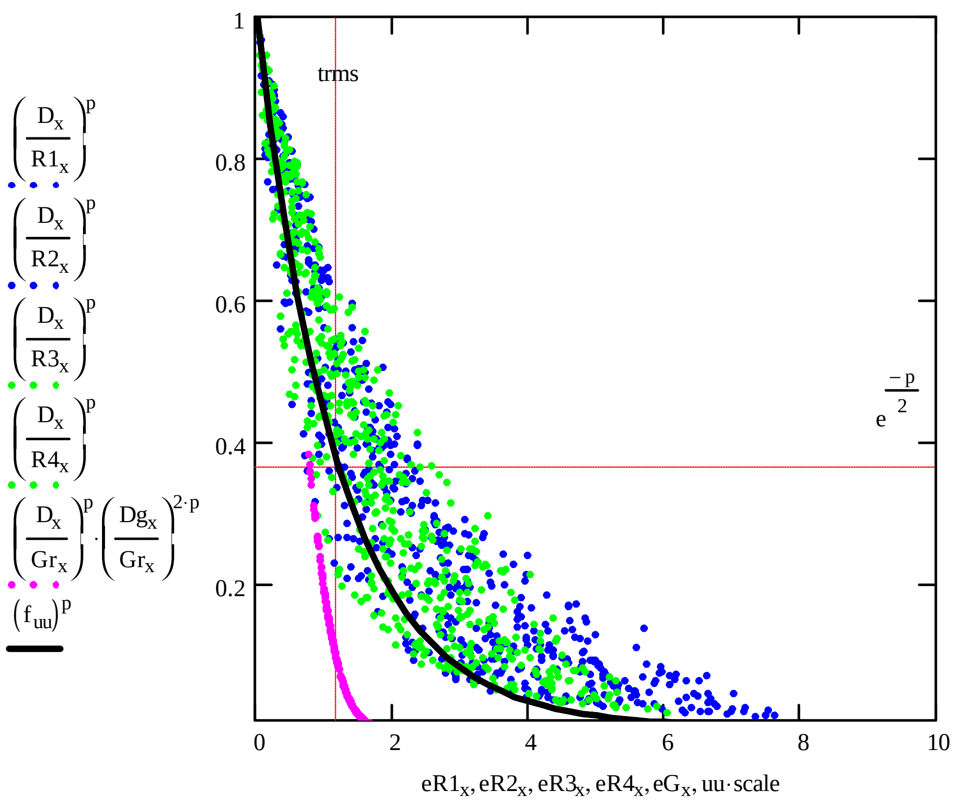

Figure 9. Energy delay profile vs. excess delay (m) for all wall reflected components compared with exponential EDP.

The "corner bank shots"

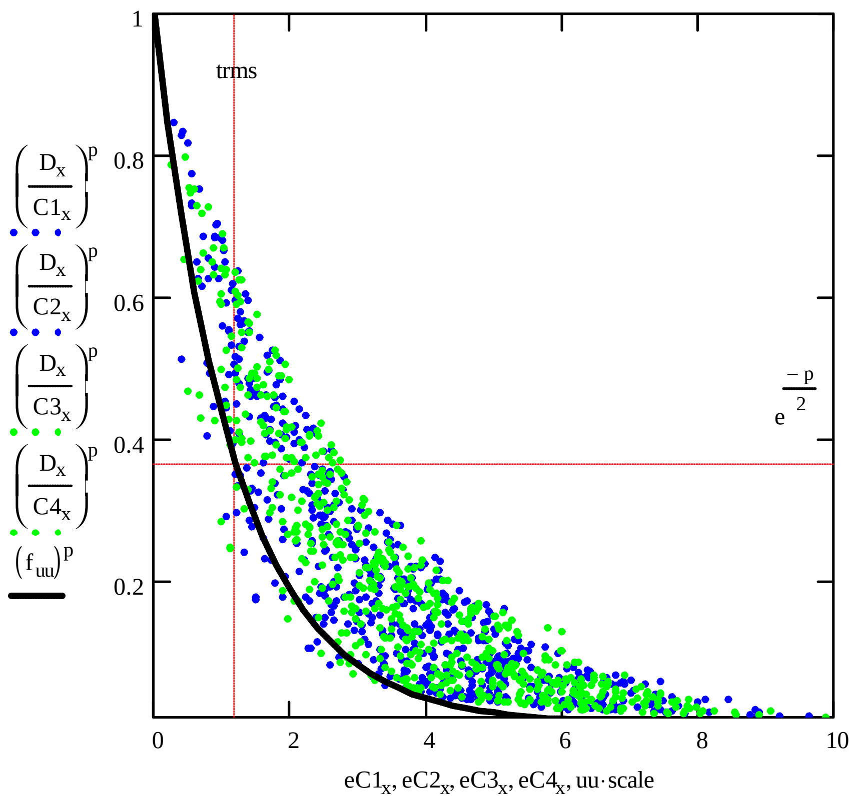

Figure 10. Energy delay profile vs. excess delay (m) for all corner reflected components compared with exponential EDP.

An exponential EDP is not a very good fit to the room calculation. Since this case is deterministic, the actual 9-reflection room model can be used.

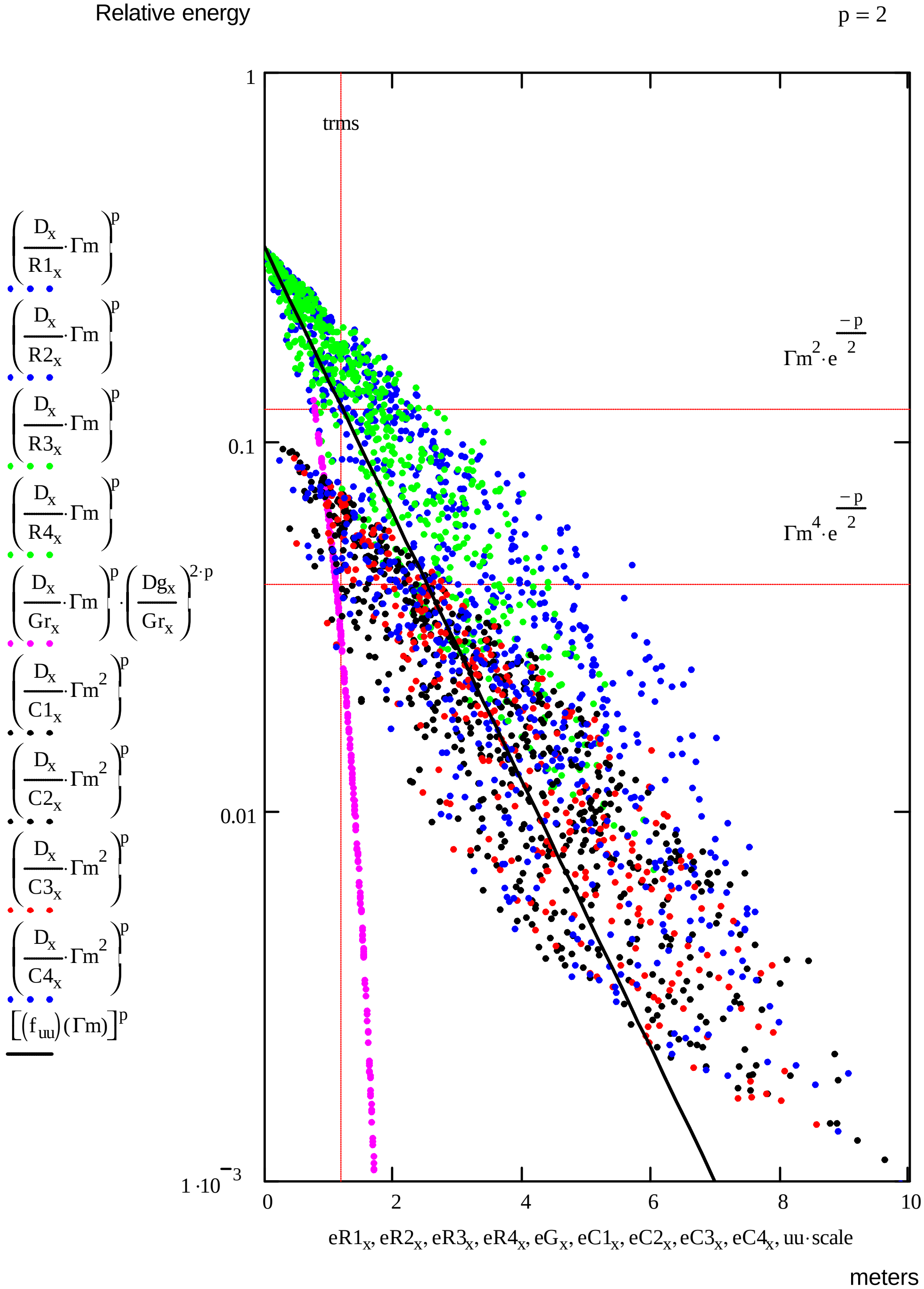

Figure 11. Multipath Energy vs. excess delay, m, for all components. Solid line represents an exponential distribution with the same delay spread.

A mean excess delay is found from

$$\mathrm{Delay}_i := \frac{eR1_i + eR2_i + eR3_i + eR4_i + eG_i \ldots + eC1_i + eC2_i + eC3_i + eC4_i}{9} \tag{21}$$

$Dmn := \mathrm{mean}(Delay)$ $\quad Dmn = 2.87$ $\quad$ m

$\mathrm{median}(Delay) = 2.921$ $\quad \frac{\mathrm{median}(Delay)}{c} \cdot 10^9 = 9.744$ $\quad$ nanoseconds

The mean ray arrival interval Ts is derived form the mean excess delay.

$$Ts := \frac{Dmn}{c} \qquad Ts \cdot 10^9 = 9.574 \quad \text{nS} \tag{22}$$

We now have all the required components for the multipath portion of a channel model.

For the line of sight (LOS) model components, we have a direct path d, and wall reflected multipath components that carry energy in addition to the free space path between the transmitter and the receiver. The i-th realization of the in-room LOS channel impulse response field spectral density is thus:

$$\begin{aligned} H_{LOSi}(t) := {} & Vfs_i(d) \ldots \\ & + \Bigg[\Gamma m \cdot \left(\frac{Dg_i}{Gr_i}\right) \cdot Vfs(d + eG) \cdot \delta\left(t - \frac{eG}{c}\right) \ldots \\ & + \Gamma m \cdot \left(\begin{aligned} & Vfs_i(d + eR1) \cdot \delta\left(t - \frac{eR1}{c}\right) \ldots \\ & + Vfs_i(d + eR1) \cdot \delta\left(t - \frac{eR2}{c}\right) \ldots \\ & + Vfs_i(d + eR1) \cdot \delta\left(t - \frac{eR3}{c}\right) \ldots \\ & + Vfs_i(d + eR1) \cdot \delta\left(t - \frac{eR4}{c}\right) \end{aligned} \right) + \Gamma m^2 \cdot \left(\begin{aligned} & Vfs_i(d + eC1) \cdot \delta\left(t - \frac{eC1}{c}\right) \ldots \\ & + Vfs_i(d + eC1) \cdot \delta\left(t - \frac{eC2}{c}\right) \ldots \\ & + Vfs_i(d + eC1) \cdot \delta\left(t - \frac{eC3}{c}\right) \ldots \\ & + Vfs_i(d + eC1) \cdot \delta\left(t - \frac{eC4}{c}\right) \end{aligned} \right) \Bigg] \end{aligned} \tag{23}$$

and the magnetic field strength spectral density at distance d is based on a spherical wave

$$Vfs(d, f) := \sqrt{EIRPsd(f) \cdot \frac{\mu \cdot c}{4\pi}} \cdot \frac{1}{d} \tag{24}$$

where EIRPsd(f) is the effective isotropically radiated power spectral density at frequency f.

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p := 1 m := 9 One, m-th, realization; normalized to direct component

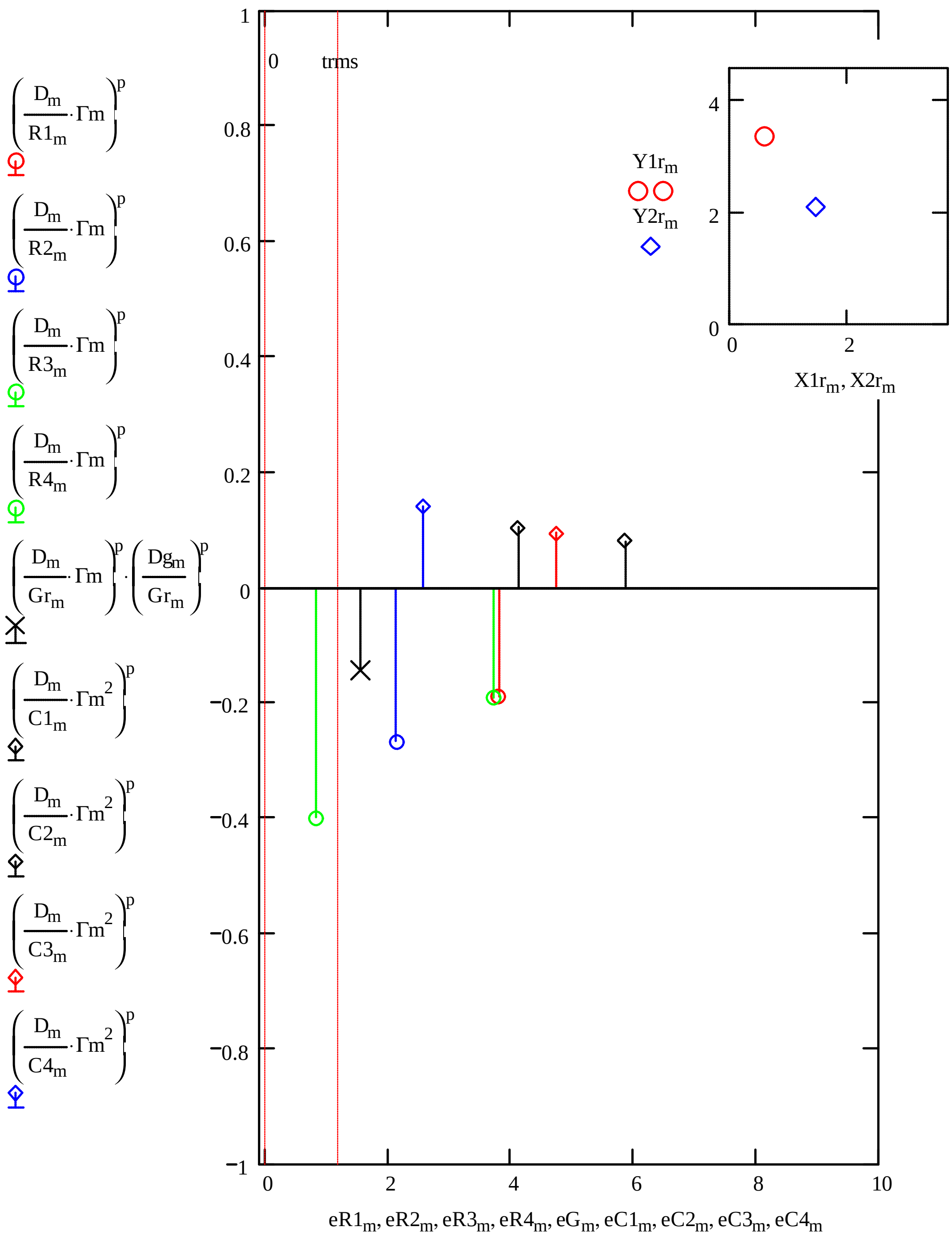

Figure 12. One particular realization of the LOS channel impulse amplitude response.

$p := 2$

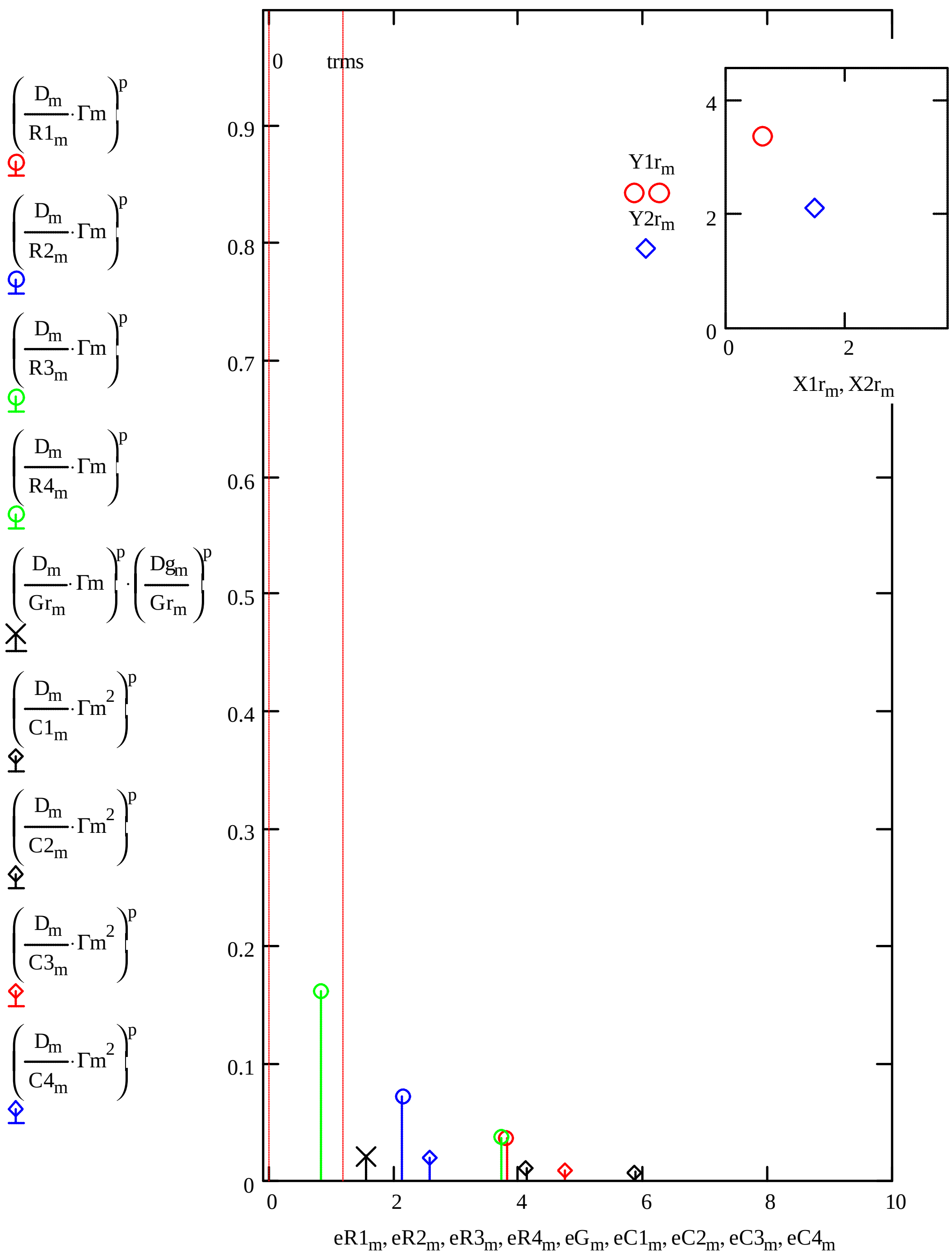

Figure 13. One particular realization of the LOS channel impulse energy response.

Plot multiple realizations of the model: $x := 0..75$ $p := 1$

$$a1_i := \left(\frac{D_i}{R1_i}\cdot\Gamma m\right)^p \quad a2_i := \left(\frac{D_i}{R2_i}\cdot\Gamma m\right)^p \quad a3_i := \left(\frac{D_i}{R3_i}\cdot\Gamma m\right)^p \quad a4_i := \left(\frac{D_i}{R4_i}\cdot\Gamma m\right)^p \quad a5_i := \left(\frac{D_i}{Gr_i}\cdot\Gamma m\right)^p\cdot\left(\frac{Dg_i}{Gr_i}\right)^p$$

$$a6_i := \left(\frac{D_i}{C1_i}\cdot\Gamma m^2\right)^p \quad a7_i := \left(\frac{D_i}{C2_i}\cdot\Gamma m^2\right)^p \quad a8_i := \left(\frac{D_i}{C3_i}\cdot\Gamma m^2\right)^p \quad a9_i := \left(\frac{D_i}{C4_i}\cdot\Gamma m^2\right)^p$$

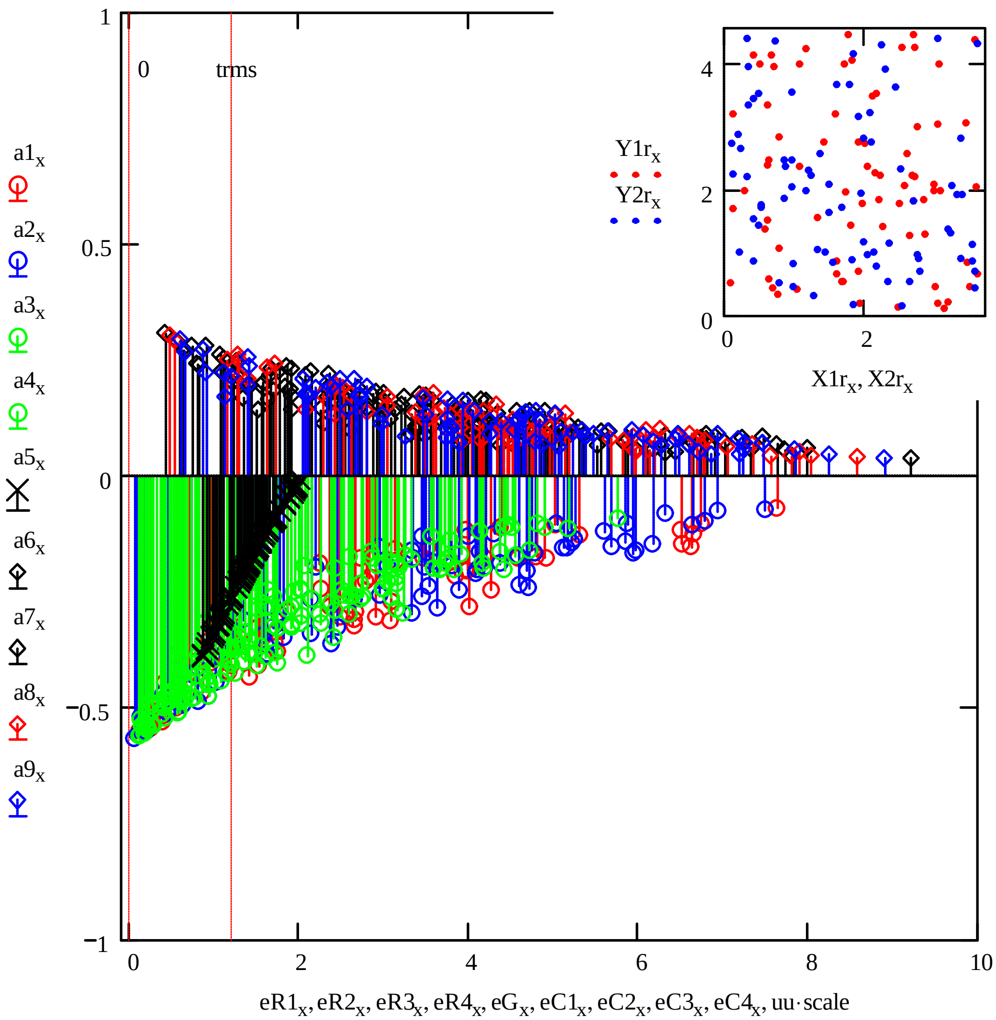

Figure 14. Multiple realizations of the LOS channel impulse amplitude responses.

The receiver antenna aperture is:

$$Ae := \frac{\frac{1.5}{4\cdot\pi}\cdot\frac{1}{f_2 - f_1}\cdot\int_{f_1}^{f_2}\left(\frac{c}{f}\right)^2\cdot\eta_{ant}(f)\cdot EIRPsd(f)\,df}{\frac{1}{f_2 - f_1}\cdot\int_{f_1}^{f_2} EIRPsd(f)\,df} \qquad (25)$$

where:

$\eta_{ant}(f)$ is the antenna efficiency as a function of frequency

$EIRPsd(f)$ is the radiated effective istropically radiated power spectral density

Thus the collected signal at the receiver is:

$$S(t) := H_{LOSi}(t)\cdot\sqrt{Ae} \qquad (26)$$

Signal S(t) contains all of the multipath components, weighted by the receiver antenna aperture, and by the receiver antenna efficiency. The method of signal detection, signal convolution the receiver filter, multiplication by the receiver template, and the signal processing will determine which and how many and how efficiently the multipath components are utilized.

The following parameters specific the UWB radio performance in a room-LOS condition:
(1) Room dimensions RoomX and RoomY, and minimum distance to a wall dt
(2) Antenna heights h1 and h2
(2) Radiated power spectral density EIRPsd(f)
(3) Receiver antenna aperture Ae
(4) Multipath signal profile S(t)
(5) Average reflection coefficient Γm

Derived parameters include:
- RMS delay spread τrms,
- the mean ray arrival rate Ts
- excess energy factor in the room is Wx

Here:

$RoomX = 3.7$	m	and	$\tau rms = 4.006\times 10^{-9}$	sec
$RoomY = 4.6$	m		$Ts = 9.574\times 10^{-9}$	sec
$h1 = 1$	m			
$h2 = 2$	m		$Wx = 1.603$	

Accounting for the total energy, the "excess" energy in the room Wx should approximately be balanced by the average wall-transmitted energy, thus: 10log[(Wx)(1 - Γm^2)] should approximately equal 0 dB.

$$10\cdot\log\left[\left(1 - \Gamma m^2\right)\cdot Wx\right] = 0.269 \quad \text{dB} \qquad (27)$$

Non-Line of Sight Multipath Model

The Jakes [Jakes 1974] model with exponential EDP will be applied, here for UWB pulses in non-line of sight (NLOS) cases. Thus the multipath impulses are exponentially distributed, their arrival interval is randomly distributed in windows of duration Ts.

Jakes Channel Model for f < 1000 MHz follows.

Let the initial delay spread equal τrms $\qquad \tau rms := 20 \cdot nanosec$

The mean ray Tm arrival interval is based on the LOS room model. A total of nine paths with a mean delay of Ts were found. Thus the mean ray arrival interval is 2Ts/9:

$$Tm := Ts \cdot \frac{2}{9} \qquad Tm = 2.127 \times 10^{-9} \qquad (28)$$

For now, we let Ts1 be artificially small by a factor of R, equivalent to R realizations of the channel model

$$R := 10$$

The maximum number of components considers is

$$Kmax := ceil\left(10 \cdot \frac{\tau rms}{Tm} \cdot R\right) \qquad Kmax = 941 \qquad k := 0..\, Kmax$$

The multipath components are randomly distributed in "bins" that are Ts wide and spaced Ts.

$$T_k := \frac{Tm}{R} \cdot (k + rnd(1)) \qquad T_0 = 8.599 \times 10^{-11} \qquad (29)$$

Channel coefficient h is normally distributed with unity standard deviation:

$$hk := rnorm(Kmax + 1, 0, 1) \qquad (30)$$

(sanity check): $\quad mean(hk) = -7.563 \times 10^{-3} \qquad stdev(hk) = 1.006$

$$\sigma a := 1 - exp\left(\frac{-Tm}{\tau rms \cdot R}\right) \qquad \sigma a = 0.011 \qquad (31)$$

$$\sigma_k := \sqrt{\sigma a} \cdot exp\left(-\frac{T_k}{\tau rms \cdot 2}\right) \qquad \sigma_0 = 0.103 \qquad (32)$$

Check the result

$$\sigma 2_k := \left(\sigma_k\right)^2 \qquad mean(\sigma 2) \cdot Kmax = 0.994 \qquad (33)$$

$$h_k := \sigma_k \cdot hk_k \qquad h2_k := \left(h_k\right)^2 \qquad mean(h2) \cdot Kmax = 0.942 \qquad (34)$$

$$Hdelay := \sqrt{\frac{\sigma a}{e}} \qquad Hdelay = 0.062 \qquad \tau rms := 20 \cdot nanosec \qquad tau := \frac{\tau rms}{nanosec}$$

$$tu := 0..200 \qquad z := \frac{-\tau rms}{nanosec} \cdot 0.5$$

Square root of power delay profile

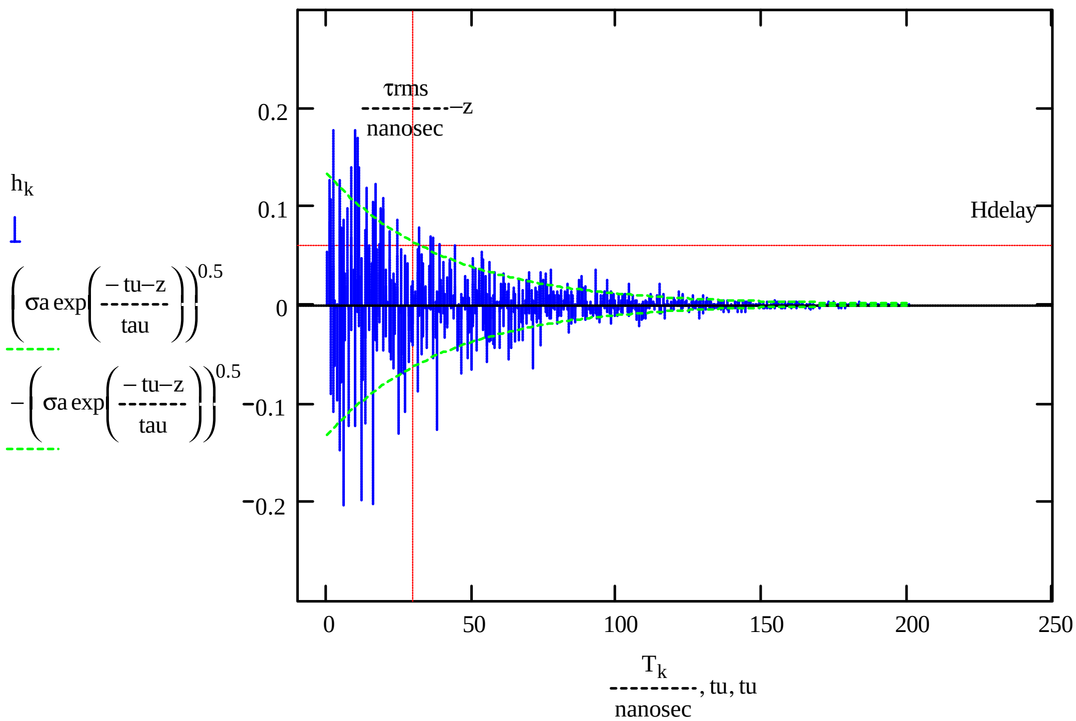

Figure 15. Multiple realizations of the NLOS channel model at a fixed distance.

NLOS multipath model: $Kmax = 941$

$$H_{NLOS}(t) := Vfs(d) \cdot \sqrt{K} \cdot \delta(0) + \left(\sqrt{1-K}\right) \cdot \sum_{k=0}^{Kmax} h_k \cdot \delta\left(t - Ts_k\right) \cdot \left(Vfs\left(d + c \cdot Ts_k\right) \cdot \delta\left(t - \frac{Ts_k}{c}\right)\right) \tag{35}$$

The receiver antenna aperture Ae is given by equation (25).

Thus the collected signal at the receiver is:

$$S_N(t) := HN_{LOSi}(t) \cdot \sqrt{Ae} \tag{36}$$

The delay spread parameter is a function of distance, [Siwiak 2003] and [Cassiolli 2002], and here is modeled by the square root of distance, see slide 34 of [IEEE802 04/504]. Thus

$$\tau rmsN(d, Dt, \tau 0) := \tau 0 \cdot \sqrt{\frac{d}{Dt}} \qquad (37)$$

A value for τ0 that approximately matches channel models CM2, CM3, and CM4 in their appropriate distances [IEEE802 02/249] is:

$$\tau 0 := 5.5 \qquad (38)$$

Thus $\tau rmsN(2, 1, \tau 0) = 7.778$

$\tau rmsN(7, 1, \tau 0) = 14.552$

$\tau rmsN(20, 1, \tau 0) = 24.597$

$\tau rmsN(50, 1, \tau 0) = 38.891$

$\tau rmsN(100, 1, \tau 0) = 55$

This will result in an average power law behavior of approximately 2.5 for a receiver not employing any rake or channel equalization technique.

Signal SN(t) contains all of the multipath components, weighted by the receiver antenna aperture, and by the receiver antenna efficiency. The method of signal detection, signal convolution the receiver filter, multiplication by the receiver template, and the signal processing will determine which and how many and how efficiently the multipath components are utilized.

The following parameters specific the UWB radio performance in a N-LOS condition:
(1) RMS delay spread parameter τ0 s mulitplied by the square root of d/Dt
(2) Mean interval between rays Tm s
(3) Fraction of energy in direct ray K
(4) Radiated power spectral density EIRPsd(f)
(5) Receiver antenna aperture Ae
(6) Multipath signal profile SN(t)

Here: $\tau 0 = 5.5$ nanosec

$\frac{Tm}{nanosec} = 2.127$ nanosec