
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		
Date Submitted	[12 September 2004] [rev1: 18 October 2004]		
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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.		
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15-04-0505-00-004a-UWB Channel Model for under 1 GHz

Introduction

The 100 MHz to 1,000 MHz channel model was designed with simplicity in mind, and with a direct physical interpretation for impulses and impulse doublets. There is no channel model in the current literature that applies to impulse doublets which spread energy over a 200% bandwidth. This model comprises two components. The first component is a *deterministic* line of sight (LOS) in-room component that captures the major reflection sources at low frequencies. These reflections are the room walls and floor for the LOS case. The ceiling is omitted. The second component is a non-line of sight (N-LOS) component which is based on the Jakes [Jakes 1974] model with exponential energy density profile (EDP) with the addition of directly radiated energy. The multipath UWB pulses and impulses are exponentially distributed, their arrival interval is randomly distributed in windows of duration T_s . The delay spread increases with distance, as is observed in experiment, thus a physically realistic propagation law naturally evolves from the model.

For both the LOS and NLOS cases a signal $S(t)$ contains all of the multipath components, weighted by the receiver antenna aperture A_e , and by the receiver antenna efficiency η_{ant} . The formulation of the multipath components, along with the time definition of UWB impulses, and the frequency dependent receiver antenna aperture and efficiency uniquely address the needs of a 100 – 1,000 MHz channel model. The method of signal detection, including the receiver filter and multiplication by the receiver template, and the signal processing will determine which and how many and how efficiently the multipath components are utilized, and how accurately ranges are determined.

The model is capable of evaluating UWB impulse radios in (1) direct free space propagation in additive white Gaussian noise (AWGN), (2) LOS conditions with multipath typical of a room, and (3) a range on N-LOS conditions with and without direct path contributions. The model output is a signal profile in time which is the input to the UWB receiver.

The full model code, rendered in Mathcad is given in the Appendix.

The Line of Sight Model

LOS attenuation is free space intergal over PSD for distances: $d < (RoomX^2 + RoomY^2)^{1/2}$ m
Where $RoomX$ and $RoomY$ are the room dimensions. Multipath is derived from a direct path and 9 primary reflections of a room model:

- 4 principal reflections from the walls
- 1 ground reflection
- 4 principal corner reflections

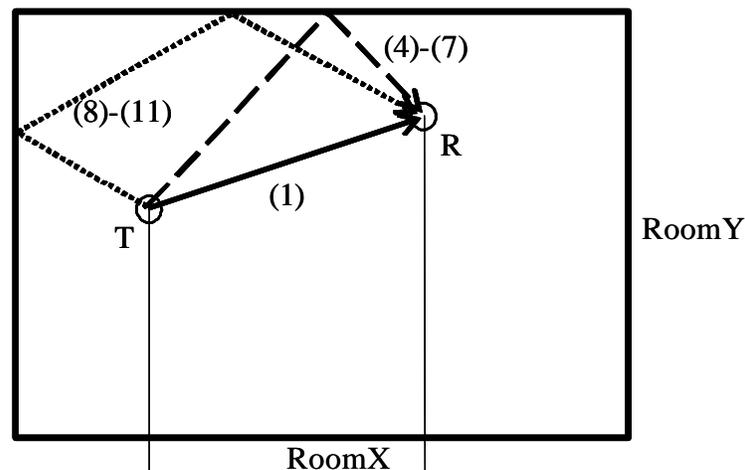
Multiple realizations are utilized by randomly selecting a transmit and a receive point in the room.

The selected points are no closer than d_t from any wall.

The LOS component of the channel model comprises 5 geometrical parameter and 3 signal parameters. These are:

- Room dimensions $RoomX$ and $RoomY$,
- Minimum distance to a wall d_t ,
- Antenna heights $h1$ and $h2$
- Average wall and floor reflection coefficient Γ_m
- Radiated power spectral density $EIRP_{sd}(f)$
- Receiver antenna aperture A_e and antenna efficiency $\eta_{ant}(f)$

Top view



Side view

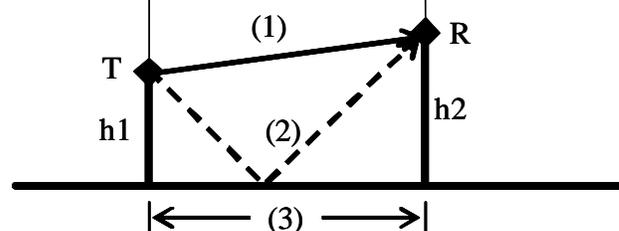


Figure 1. LOS components in a room of dimensions $RoomX$ by $RoomY$.

The reflection coefficient is derived from [Honch 1992]. Figure 1 shows the signal paths between a transmit antenna T and a receive antenna R in an LOS condition in the room. Total energy is

accounted for in the room. The "excess" energy in the room should be balanced by the average wall-transmitted energy. The signal paths are:

- Direct path given by Equation (1),
- Ground (floor) reflection given by (2),
- Single wall reflections given by (4) through (7),
- Double wall reflections (corner bounces) given by (8) through (11).

The derived parameters include:

- Multipath signal profile $S(t)$
- RMS delay spread τ_{rms} ,
- the mean ray arrival rate T_s
- excess energy factor in the room is W_x

The apparent total energy received at R is greater than would be obtained from a single path free space transmission from T because the reflections direct additional time dispersed signal copies to the receiver. It is important to note that the wave propagation along each path is governed by the physics of an expanding spherical wave, thus the energy in each path attenuates as the square of distance. The case resembles a Ricean distribution comprising significant energy in a direct path followed by a decaying multipath profile. On the average, in a 3.7 m by 4.6 m room, the energy in the multipath components is 2.2 dB below the direct path energy, thus the total available energy is 2 dB higher than contained in just the direct path. The statistics of the multipath components are nearly, but not quite described by a Rayleigh distribution.

Energy conservation dictates that the total energy leaving the room should equal the energy transmitted. This can be approximately checked by observing the product of the excess energy factor with the average transmission coefficient $W_x[1 - \Gamma_m^2]$ which should be approximately one. The modeled case verifies this within approximately 0.26 dB.

The LOS model is specified by Equation (26), and supported by Equations (23), (24), and (25) in the Appendix.

Non-Line of Sight Multipath Model:

The non line of sight path is assumed to be described by a modified Ricean EDP. As such a total of 3 Ricean parameters plus an additional distance parameter totally specify the multipath profile. The multipath increases with distance, see [Siwiak 2003] and [Cassioli 2002], and here is modeled by square root of distance d/D_t , scaled by the constant τ_0 . Energy dispersed into and increasingly longer multipath profile naturally results in an increase in the power law of propagation attenuation. Thus the increase by the square root of distance results in an overall inverse 2.5 power of distance for multipath components. Rather than a non-physical phase

parameter, a random distance variation within the mean interval T_m is used to define the time that multipath components arrive at the receiver. Total energy propagations as an expanding spherical wave, so the basic propagation is inverse square law. The unit energy is allocated a fraction K_F for the direct component, if any, and $(1-K_F)$ for the multipath energy.

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

- RMS delay spread parameter τ_0 s, and initial distance D_t
- Mean interval between rays T_m s
- Fraction of energy in direct component K_F
- Radiated power spectral density EIRPsd(f)
- Receiver antenna aperture A_e and antenna efficiency $\eta_{ant}(f)$

The channel model signal profile is

- Multipath signal amplitude profile $S_N(t)$

The recommended parameters are $\tau_0=5.5$ ns, and $D_t=1$ m to approximately match the NLOS parameters of CM2, CM3, and CM4 in [IEEE802 02/249] at the required distances, see slide 34 of [IEEE802 04/504]. Direct path energy fraction K_F is a parameter that takes on values between 0 for a fully diffuse multipath and 1 for a pure line of sight free space path. K_F is related to the usual Ricean K -factor by $K_F=K/(1+K)$ or equivalently $K=K_F/(1-K_F)$, where K_F is in the range $[0, 1]$ and correspondingly K takes on the range $[0, \infty]$. Recommended values of K_F are 0 (a fully diffused multipath), 0.3 (half the reflected energy fraction in the LOS case), and 0.6. $K_F=1$ should be used to establish the radio performance in AWGN.

For both channel model components, the signal $S_N(t)$ 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 N-LOS model is specified by Equation (36), and supported by Equations (23), (24), (35) and (37) in the Appendix.

References

- [Honch 1992] W. Honcharenko, 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.
- [Cassioli 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-uwband-no-response-eq-sop.ppt

APPENDIX

Mathcad code for the 100 – 1,000 MHz Channel model Components

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

Preliminary Draft: 10 September 2004, rev0 12 October 2004, rev1 18 October 2003

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 T_s .

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: $d < (\text{RoomX}^2 + \text{RoomY}^2)^{1/2}$ m

- Direct plus with Γ^2 power additional single reflection multipaths; Γ^4 from 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 Γ_m

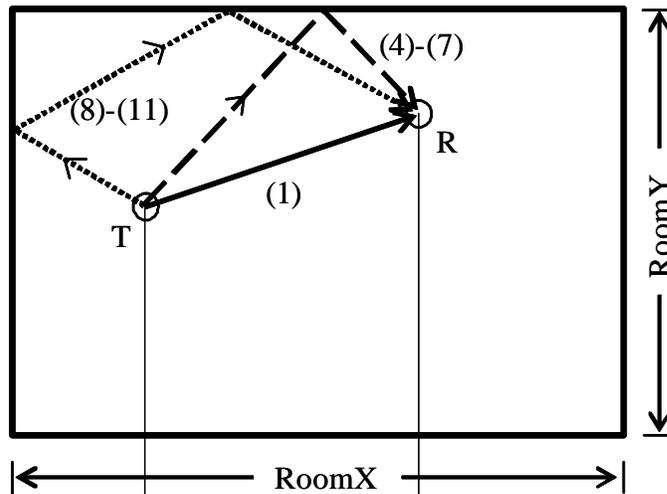
Derived parameters include:

- RMS delay spread τ_{rms} ,
- the mean ray arrival rate T_s
- excess energy factor in the room is W_x

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.

Top view



Side view

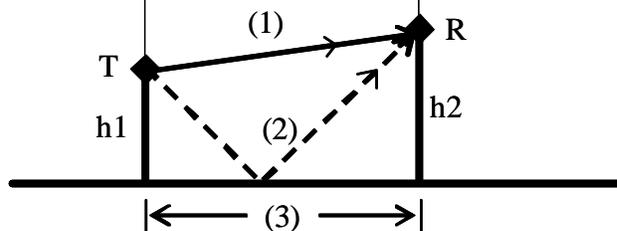


Figure 1. Top and side views of signal paths inside a room.

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 T_s . The delay spread parameter is a function of distance, [Siwiak 2003] and [Cassioli 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 τ_{0s} and distance D_t
- (2) Mean interval between rays T_m
- (3) Fraction of energy in direct ray K_f
- (4) Radiated power spectral density $EIRP_{sd}(f)$
- (5) Receiver antenna aperture A_e
- (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.

References:

[Honch 1992] W. Honcharenko, 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.

[Cassioli 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-uw-b-no-response-eq-sop.ppt

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

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

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

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

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

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

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

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

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

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

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 := 200000 $i := 0..Nrnd$

$$\begin{aligned} X1r_i &:= \text{md}(\text{RoomX} - 2 \cdot \text{dt}) + \text{dt} & Y1r_i &:= \text{md}(\text{RoomY} - 2 \cdot \text{dt}) + \text{dt} \\ X2r_i &:= \text{md}(\text{RoomX} - 2 \cdot \text{dt}) + \text{dt} & Y2r_i &:= \text{md}(\text{RoomY} - 2 \cdot \text{dt}) + \text{dt} \end{aligned} \quad (12)$$

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 $eR1_i, eR2_i, eR3_i, eR4_i$; and $eC1, eC2, eC3, eC4$.

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

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

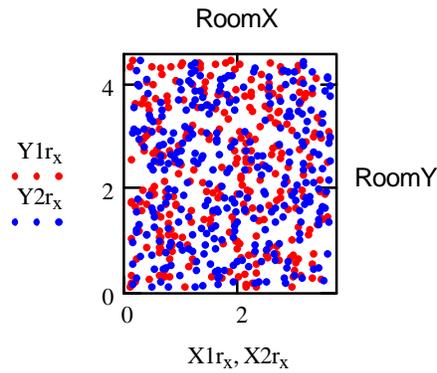


Figure 2. A sampling of the total points (X1, Y1) and (X2, Y2).

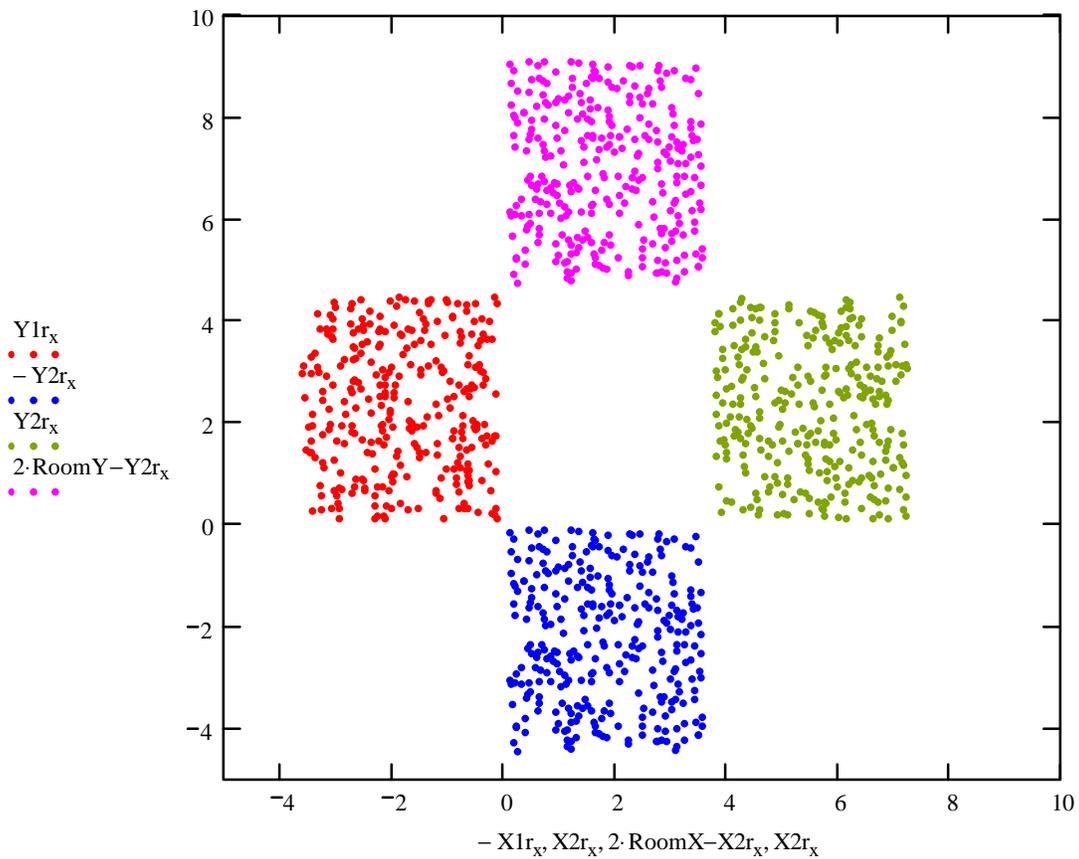


Figure 3. Images in the room walls of the reflection points. C1 are lower left and C2 are lower right, C3 are upper right and C4 are upper left.

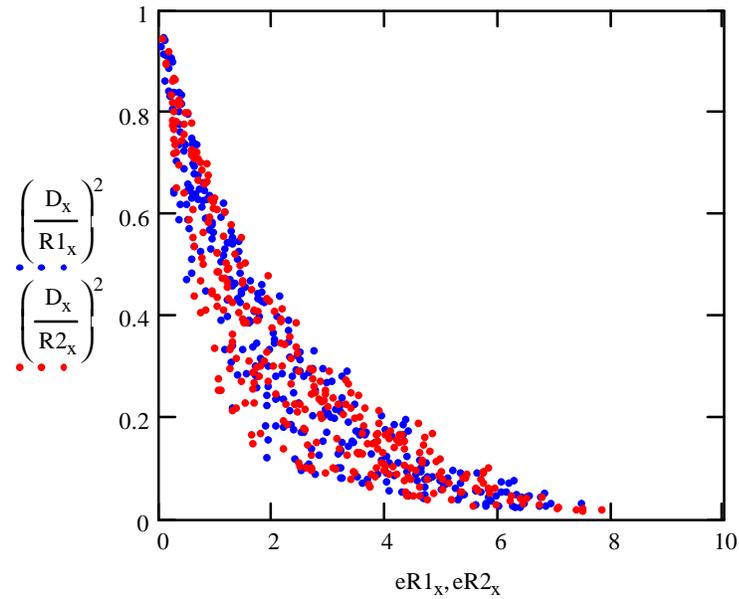


Figure 4. Energy delay profile (EDP) vs. excess delay: R1, R2. The excess delays is associated with the Y dimension of the room.

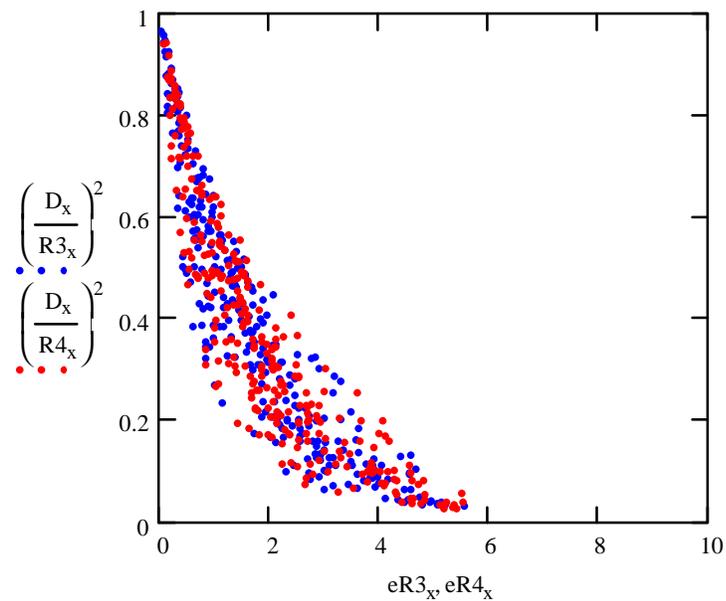


Figure 5. Energy delay profile vs. excess delay, R3, R4. The excess delays are associated with the X dimension of the room.

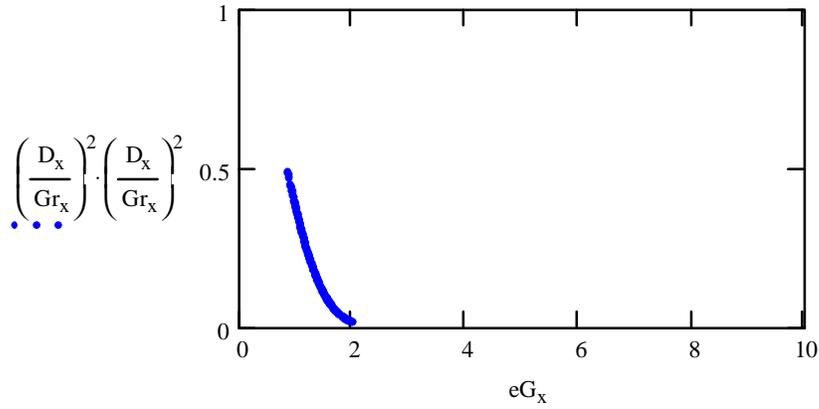


Figure 6. Energy delay profile vs. excess delay, for the ground reflection Gr .

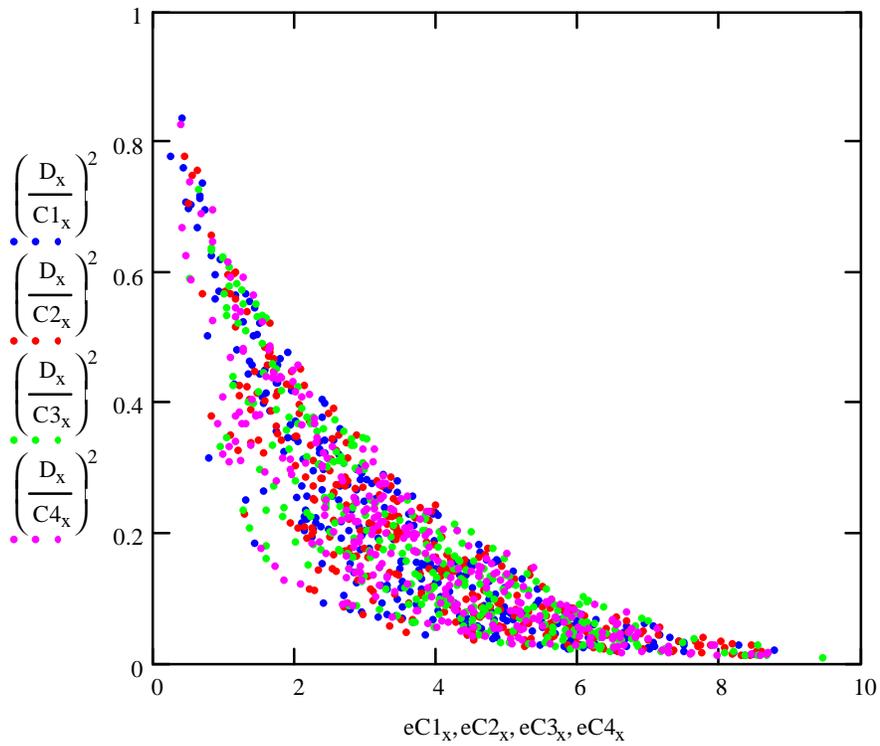


Figure 7. Energy delay profile vs. excess delay, for the corner reflections.

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

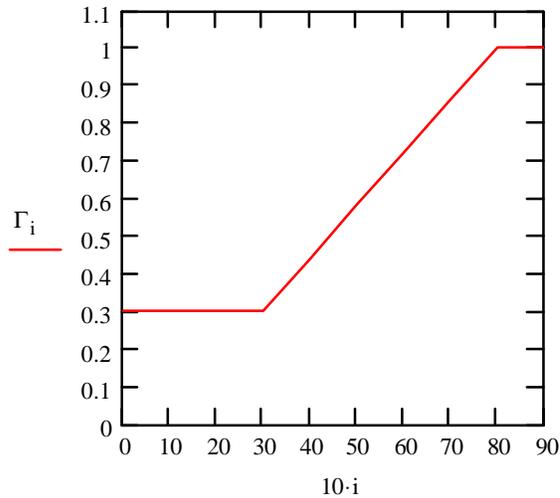


Figure 8. Reflection coefficient vs. incident angle for concrete and plaster board walls. [Honch 1992].

$$\Gamma_m := -\text{mean}(\Gamma) \quad \Gamma_m = -0.58 \quad (14)$$

$$20 \cdot \log(|\Gamma_m|) = -4.731$$

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 $T_m := 1 + \Gamma_m \quad 20 \cdot \log(T_m) = -7.535$

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:

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

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

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 h_1 and h_2 .

The rms delay spread τ_{rms} 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

$$\begin{aligned} \tau_{m_1} := & \left[\left(\frac{D_i}{R_{1_i}} \right)^2 \cdot eR_{1_i} + \left(\frac{D_i}{R_{2_i}} \right)^2 \cdot eR_{2_i} + \left(\frac{D_i}{R_{3_i}} \right)^2 \cdot eR_{3_i} + \left(\frac{D_i}{R_{4_i}} \right)^2 \cdot eR_{4_i} + \left(\frac{D_{g_i}}{Gr_i} \right)^2 \cdot \left(\frac{D_i}{Gr_i} \right)^4 \cdot eG_i \right] \cdot \Gamma m^2 \dots \\ & + \left[\left(\frac{D_i}{C_{1_i}} \right)^2 \cdot eC_{1_i} + \left(\frac{D_i}{C_{2_i}} \right)^2 \cdot eC_{2_i} + \left(\frac{D_i}{C_{3_i}} \right)^2 \cdot eC_{3_i} + \left(\frac{D_i}{C_{4_i}} \right)^2 \cdot eC_{4_i} \right] \cdot \Gamma m^4 \end{aligned} \quad (16)$$

$$\begin{aligned} \tau_{m2_i} := & \left[\left(\frac{D_i}{R_{1_i}} \right)^2 \cdot (eR_{1_i})^2 + \left(\frac{D_i}{R_{2_i}} \right)^2 \cdot (eR_{2_i})^2 + \left(\frac{D_i}{R_{3_i}} \right)^2 \cdot (eR_{3_i})^2 \dots \right] \cdot \Gamma m^2 \dots \\ & + \left[\left(\frac{D_i}{R_{4_i}} \right)^2 \cdot (eR_{4_i})^2 + \left(\frac{D_{g_i}}{Gr_i} \right)^2 \cdot \left(\frac{D_i}{Gr_i} \right)^4 \cdot (eG_i)^2 \right] \\ & + \left[\left(\frac{D_i}{C_{1_i}} \right)^2 \cdot (eC_{1_i})^2 + \left(\frac{D_i}{C_{2_i}} \right)^2 \cdot (eC_{2_i})^2 + \left(\frac{D_i}{C_{3_i}} \right)^2 \cdot (eC_{3_i})^2 + \left(\frac{D_i}{C_{4_i}} \right)^2 \cdot (eC_{4_i})^2 \right] \cdot \Gamma m^4 \end{aligned} \quad (17)$$

$$\begin{aligned} W_i := & \left[\left(\frac{D_i}{R_{1_i}} \right)^2 + \left(\frac{D_i}{R_{2_i}} \right)^2 + \left(\frac{D_i}{R_{3_i}} \right)^2 + \left(\frac{D_i}{R_{4_i}} \right)^2 + \left(\frac{D_{g_i}}{Gr_i} \right)^2 \cdot \left(\frac{D_i}{Gr_i} \right)^4 \right] \cdot \Gamma m^2 \dots \\ & + \left[\left(\frac{D_i}{C_{1_i}} \right)^2 + \left(\frac{D_i}{C_{2_i}} \right)^2 + \left(\frac{D_i}{C_{3_i}} \right)^2 + \left(\frac{D_i}{C_{4_i}} \right)^2 \right] \cdot \Gamma m^4 \end{aligned} \quad (18)$$

The "total" energy in the room is W_x times the direct path energy:

$$W_x := \text{mean}(W) + 1 \quad 10 \cdot \log(W_x) = 2.041 \quad \text{dB}$$

$$10 \cdot \log(W_x - 1) = -2.218 \quad \text{dB}$$

$$\tau_{2rms_i} := \sqrt{\frac{\tau_{m2_i}}{W_i} - \left(\frac{\tau_{m_1}}{W_i} \right)^2} \quad \tau_{rms} := \text{mean}(\tau_{2rms}) \quad (19)$$

$$\max(\tau_{2rms}) = 1.759 \quad \min(\tau_{2rms}) = 0.156 \quad \tau_{rms} = 1.203 \quad \text{meters}$$

Finally the rms delay spread τ_{rms} is found

$$\tau_{rms} := \frac{\tau_{rms}}{c} \tag{20}$$

and its value for the selected case is

$$\tau_{rms} \cdot 10^9 = 4.014 \quad \text{nS} \quad \frac{\max(\tau_{2rms})}{c} \cdot 10^9 = 5.866 \quad \text{nS}$$

Figure 5 shows the EDPs vs. excess delays for all three sets of reflections. Note the ground reflections (magenta) follow a narrow range of possibilities. An exponential EDP with delay spread τ_{rms} 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.

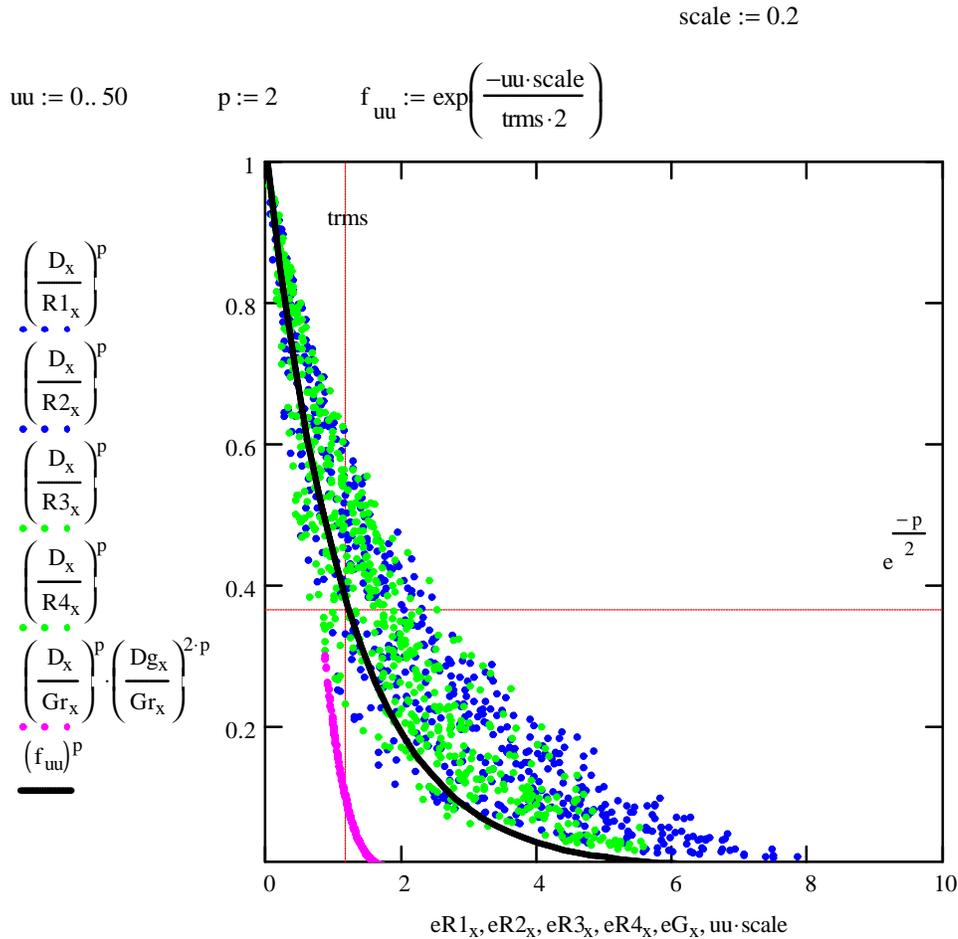


Figure 9. Energy delay profile vs. excess delay (m) for all wall reflected components compared with exponential EDP.

The "corner bank shots"

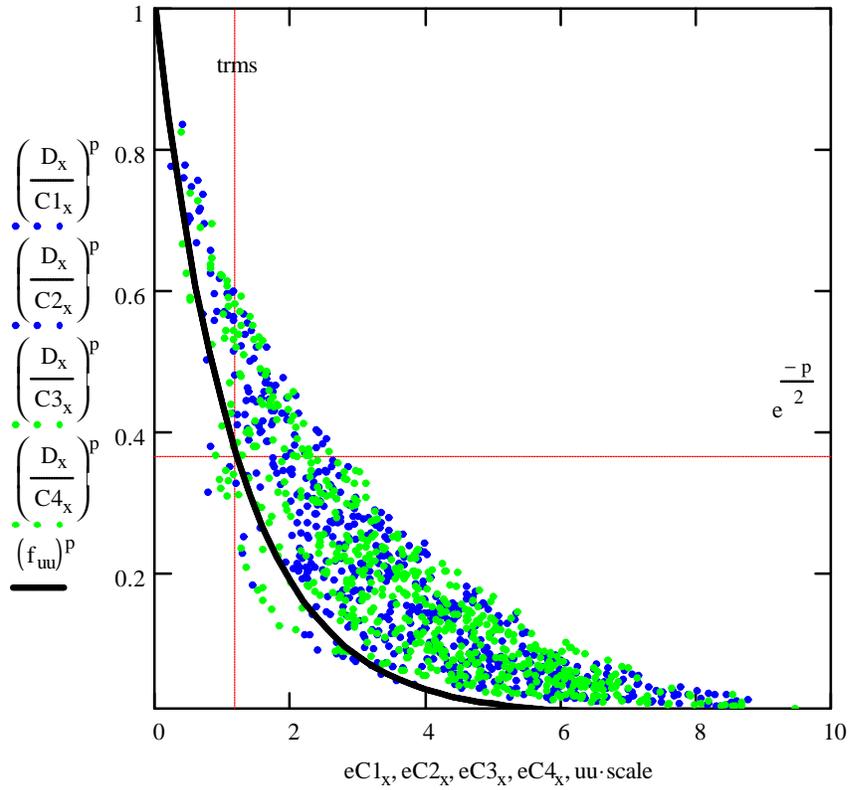


Figure 10. Energy delay profile vs. excess delay (m) for all corner reflected components compared with exponential EDP.

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.

Relative energy

p = 2

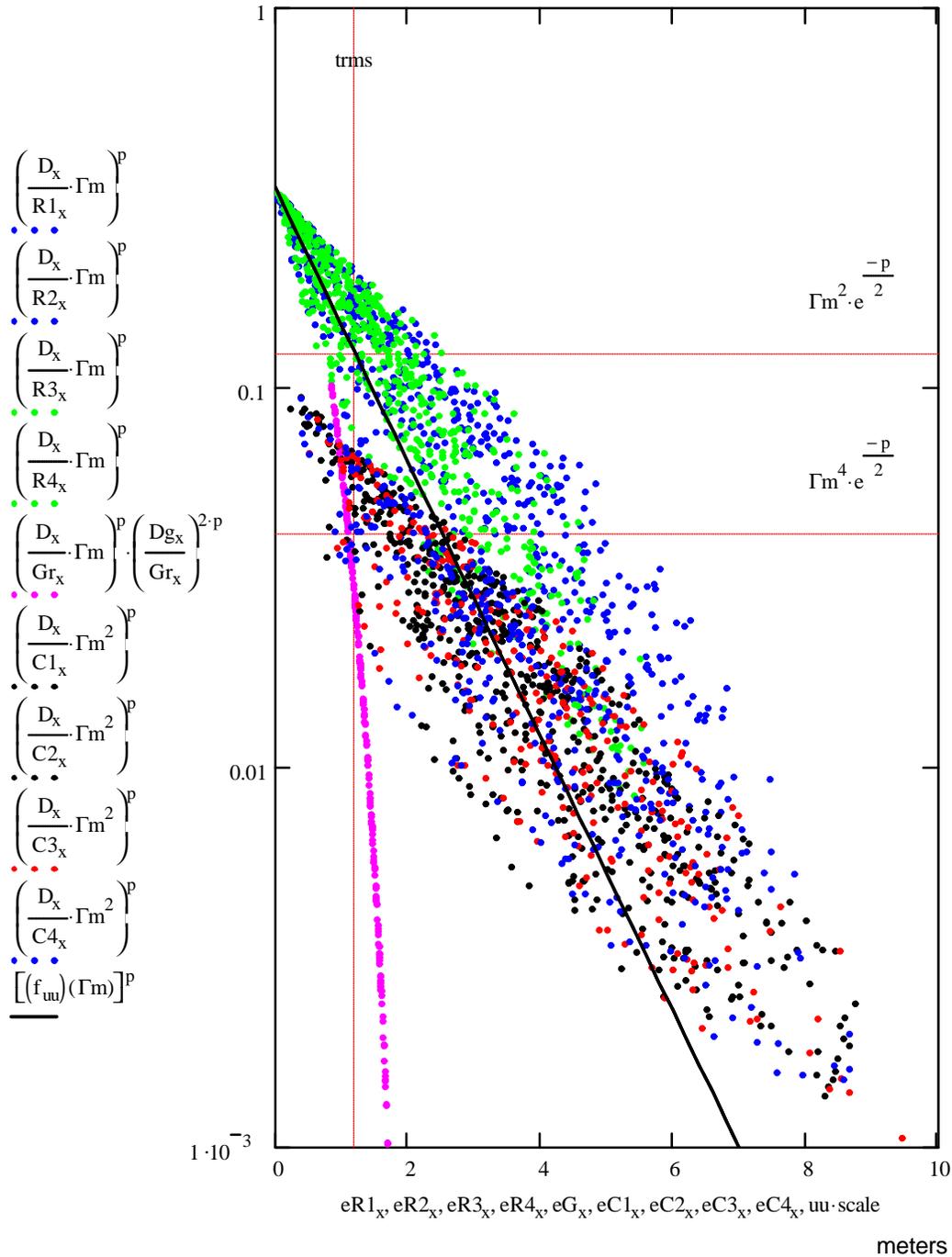


Figure 11. Multipath Energy vs. excess delay, m, for all components. Solid line represents an exponential distribution with the same delay spread.

A mean excess delay is found from

$$\text{Delay}_i := \frac{eR_{1_i} + eR_{2_i} + eR_{3_i} + eR_{4_i} + eG_{1_i} \dots + eC_{1_i} + eC_{2_i} + eC_{3_i} + eC_{4_i}}{9} \quad (21)$$

$$D_{mn} := \text{mean}(\text{Delay}) \quad D_{mn} = 2.878 \quad \text{m}$$

$$\text{median}(\text{Delay}) = 2.933 \quad \frac{\text{median}(\text{Delay})}{c} \cdot 10^9 = 9.782 \quad \text{nanoseconds}$$

The mean ray arrival interval T_s is derived from the mean excess delay.

$$T_s := \frac{D_{mn}}{c} \quad T_s \cdot 10^9 = 9.6 \quad \text{nS} \quad (22)$$

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:

$$H_{\text{LOS}_i}(t) := Vfs_i(d) \dots \left[\begin{array}{l} + \Gamma m \left(\frac{Dg_i}{Gr_i} \right) \cdot Vfs(d + eG) \cdot \delta \left(t - \frac{eG}{c} \right) \dots \\ + \Gamma m \left(\begin{array}{l} Vfs_i(d + eR1) \cdot \delta \left(t - \frac{eR1}{c} \right) \dots \\ + Vfs_i(d + eR1) \cdot \delta \left(t - \frac{eR2}{c} \right) \dots \\ + Vfs_i(d + eR1) \cdot \delta \left(t - \frac{eR3}{c} \right) \dots \\ + Vfs_i(d + eR1) \cdot \delta \left(t - \frac{eR4}{c} \right) \dots \end{array} \right) + \Gamma m^2 \cdot \left(\begin{array}{l} Vfs_i(d + eC1) \cdot \delta \left(t - \frac{eC1}{c} \right) \dots \\ + Vfs_i(d + eC1) \cdot \delta \left(t - \frac{eC2}{c} \right) \dots \\ + Vfs_i(d + eC1) \cdot \delta \left(t - \frac{eC3}{c} \right) \dots \\ + Vfs_i(d + eC1) \cdot \delta \left(t - \frac{eC4}{c} \right) \dots \end{array} \right) \end{array} \right] \quad (23)$$

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

$$Vfs(d, f) := \sqrt{\text{EIRPs}_d(f) \cdot \frac{\mu \cdot c}{4\pi} \cdot \frac{1}{d}} \quad (24)$$

where $\text{EIRPs}_d(f)$ is the effective isotropically radiated power spectral density at frequency f .

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

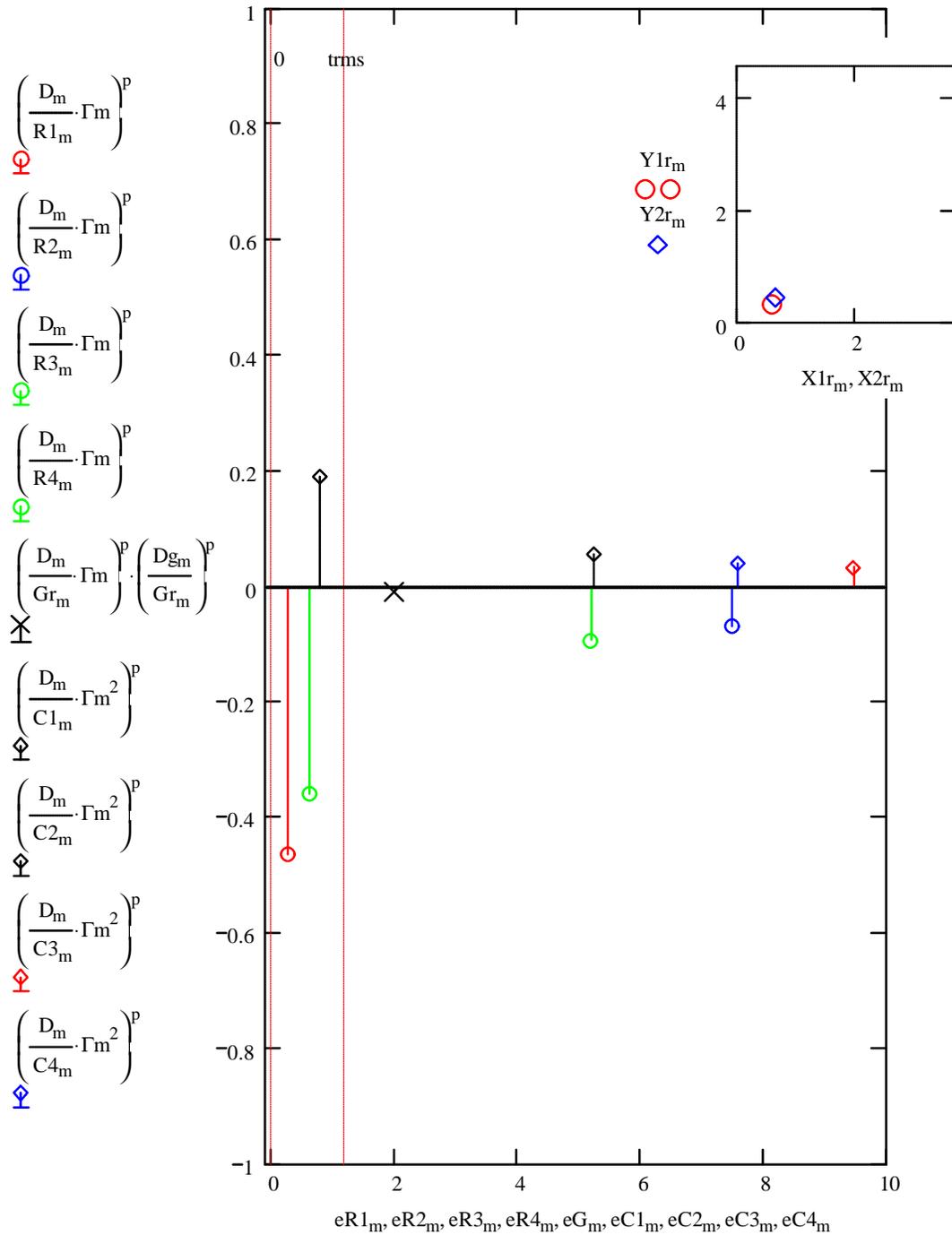


Figure 12. One particular realization of the LOS channel impulse amplitude response.

p := 2

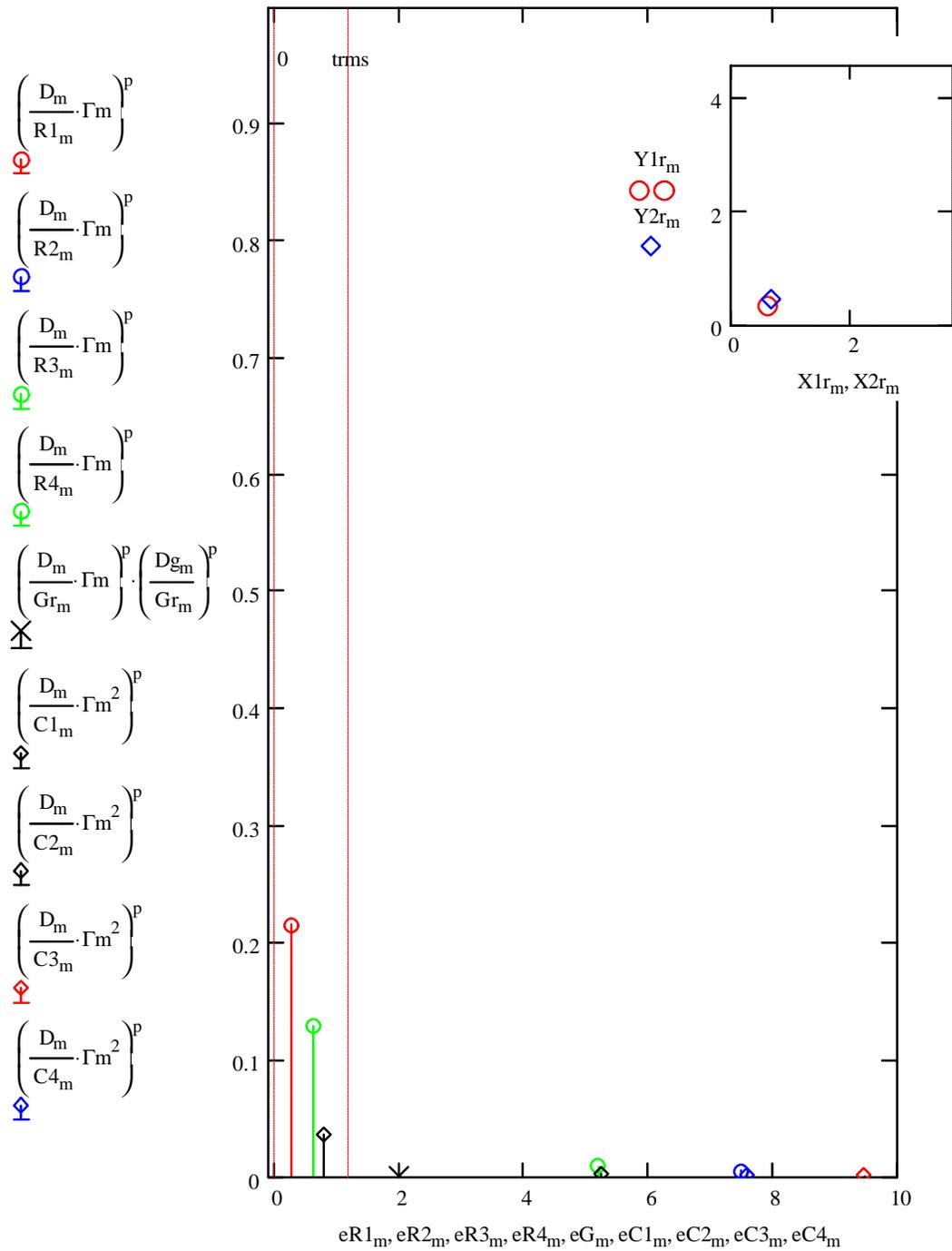


Figure 13. One particular realization of the LOS channel impulse energy response.

Plot multiple realizations of the model:

$x := 0..75$

$p := 1$

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

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

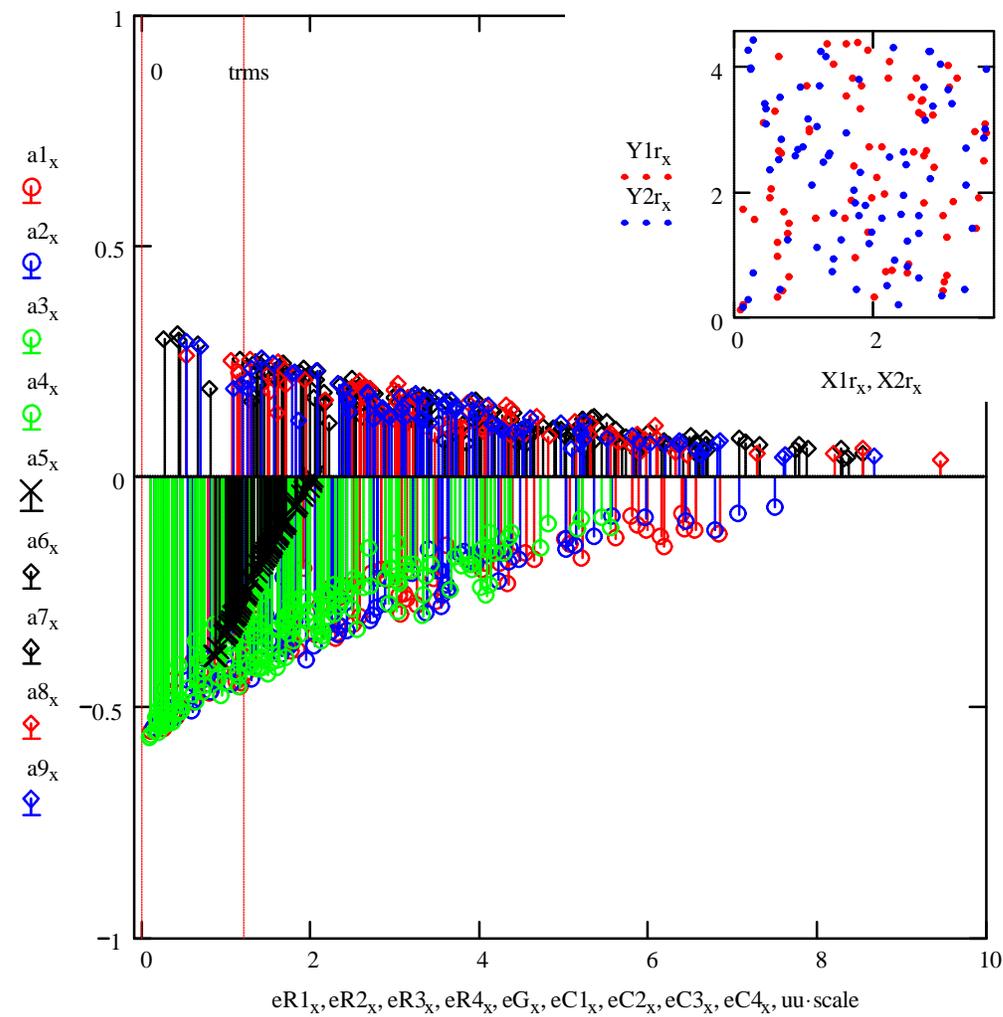


Figure 14. Multiple realizations of the LOS channel impulse amplitude responses.

The receiver antenna aperture is:

$$A_e := \frac{\frac{1.5}{4\pi} \cdot \frac{1}{f_2 - f_1} \cdot \int_{f_1}^{f_2} \left(\frac{c}{f}\right)^2 \cdot \eta_{\text{ant}}(f) \cdot \text{EIRPs}_d(f) \, df}{\frac{1}{f_2 - f_1} \cdot \int_{f_1}^{f_2} \text{EIRPs}_d(f) \, df} \quad (25)$$

where:

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

$\text{EIRPs}_d(f)$ is the radiated effective isotropically radiated power spectral density

Thus the collected signal at the receiver is:

$$S(t) := H_{\text{LOS}}(t) \cdot \sqrt{A_e} \quad (26)$$

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 d_t
- (2) Antenna heights h_1 and h_2
- (2) Radiated power spectral density $\text{EIRPs}_d(f)$
- (3) Receiver antenna aperture A_e
- (4) Multipath signal profile $S(t)$
- (5) Average reflection coefficient Γ_m

Derived parameters include:

- RMS delay spread τ_{rms} ,
- the mean ray arrival rate T_s
- excess energy factor in the room is W_x

Here:	RoomX = 3.7	m	and	$\tau_{\text{rms}} = 4.014 \times 10^{-9}$	sec
	RoomY = 4.6	m		$T_s = 9.6 \times 10^{-9}$	sec
	$h_1 = 1$	m			
	$h_2 = 2$	m		$W_x = 1.6$	

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

$$10 \cdot \log \left[(1 - \Gamma_m^2) \cdot W_x \right] = 0.26 \quad \text{dB} \quad (27)$$

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 T_s .

Jakes Channel Model for $f < 1000$ MHz follows.

To test the equations, let the initial delay spread equal τ_{rms} where $\tau_{rms} := 20 \cdot \text{nanosec}$

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

$$T_m := T_s \cdot \frac{2}{9} \quad T_m = 2.133 \times 10^{-9} \quad (28)$$

For now, we let T_{s1} 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

$$K_{max} := \text{ceil}\left(10 \cdot \frac{\tau_{rms}}{T_m} \cdot R\right) \quad K_{max} = 938 \quad k := 0..K_{max}$$

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

$$T_k := \frac{T_m}{R} \cdot (k + \text{rnd}(1)) \quad T_0 = 2.052 \times 10^{-10} \quad (29)$$

Channel coefficient h is normally distributed with unity standard deviation:

$$h_k := \text{norm}(K_{max} + 1, 0, 1) \quad (30)$$

(sanity check): $\text{mean}(h_k) = -0.035$ $\text{stdev}(h_k) = 1.026$

$$\sigma_a := 1 - \exp\left(\frac{-T_m}{\tau_{rms} \cdot R}\right) \quad \sigma_a = 0.011 \quad (31)$$

$$\sigma_k := \sqrt{\sigma_a} \cdot \exp\left(\frac{T_k}{\tau_{rms} \cdot 2}\right) \quad \sigma_0 = 0.102 \quad (32)$$

Check the result

$$\sigma_{2k} := (\sigma_k)^2 \quad \text{mean}(\sigma_{2k}) \cdot K_{max} = 0.993 \quad (33)$$

$$h_k := \sigma_k \cdot h_k \quad h_{2k} := (h_k)^2 \quad \text{mean}(h_{2k}) \cdot K_{max} = 1.222 \quad (34)$$

$$H_{\text{delay}} := \sqrt{\frac{\sigma_a}{e}} \quad H_{\text{delay}} = 0.062 \quad \tau_{\text{rms}} := 20 \cdot \text{nanosec} \quad \tau := \frac{\tau_{\text{rms}}}{\text{nanosec}}$$

$$t_u := 0..200 \quad z := \frac{-\tau_{\text{rms}}}{\text{nanosec}} \cdot 0.5$$

Square root of power delay profile

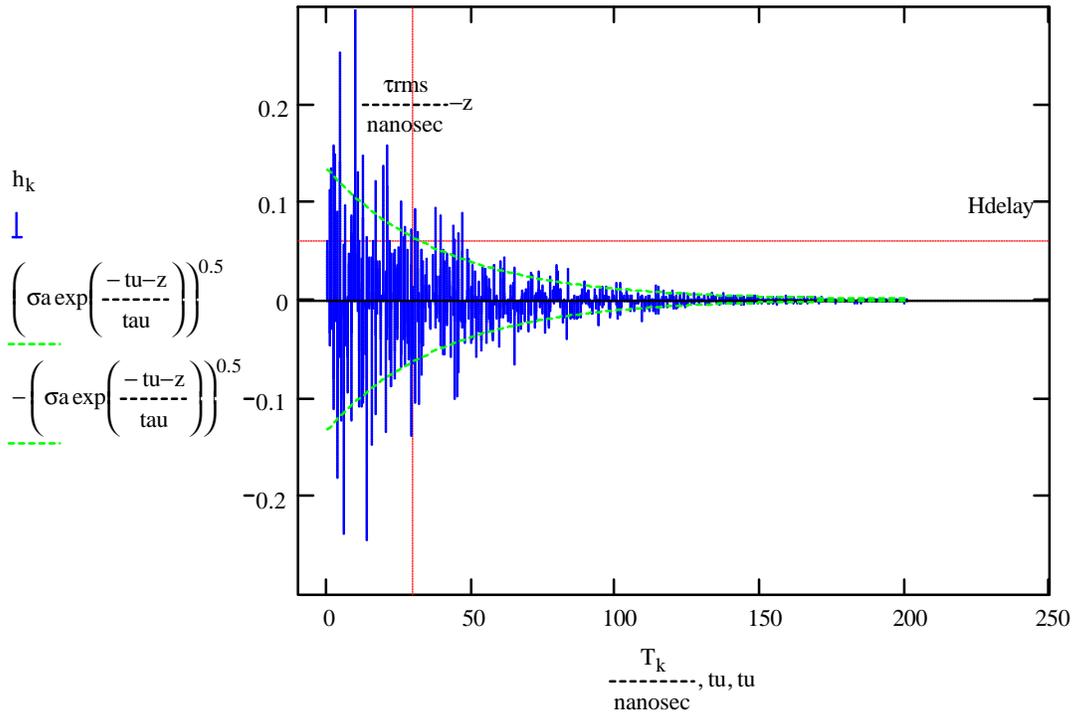


Figure 15. Multiple realizations of the NLOS channel model at a fixed distance.

NLOS multipath model: $K_{\text{max}} = 938$

$$H_{\text{NLOS}}(t) := \sqrt{K_f} \cdot \delta(0) + \left(\sqrt{1 - K_f} \right) \cdot \sum_{k=0}^{K_{\text{max}}} h_k \cdot \delta(t - T_{s_k}) \cdot \left(\sqrt{K_f} \cdot \delta\left(t - \frac{T_{s_k}}{c}\right) \right) \quad (35)$$

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

Thus the collected signal at the receiver is:

$$S_N(t) := H_{\text{NLOS}}(t) \cdot \sqrt{A_e} \quad (36)$$

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

$$\tau_{\text{rmsN}}(d, D_t, \tau_0) := \tau_0 \sqrt{\frac{d}{D_t}} \quad (37)$$

A value for τ_0 and D_t that approximately match channel models CM2, CM3, and CM4 in their appropriate distances [IEEE802 02/249] is:

$$\tau_0 := 5.5 \quad D_t := 1 \quad (38)$$

Thus $\tau_{\text{rmsN}}(2, D_t, \tau_0) = 7.778$

$$\tau_{\text{rmsN}}(7, D_t, \tau_0) = 14.552$$

$$\tau_{\text{rmsN}}(20, D_t, \tau_0) = 24.597$$

$$\tau_{\text{rmsN}}(50, D_t, \tau_0) = 38.891$$

$$\tau_{\text{rmsN}}(100, D_t, \tau_0) = 55$$

The choice of τ_{rms} increasing as the squareroot of distance will result in an average power law behavior of approximately 2.5 for a receiver not employing a rake or channel equalization technique.

Signal $S_N(t)$ 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 τ_0 s multiplied by the square root of d/D_t
- (2) Mean interval between rays T_m s
- (3) Fraction of energy in direct ray K_f
- (4) Radiated power spectral density $EIRP_{sd}(f)$
- (5) Receiver antenna aperture A_e
- (6) Multipath signal profile $S_N(t)$

The Ricean K factor and K_f are related by: $K_f = K/(K+1)$, or equivalently $K = K_f/(1-K_f)$, where K_f takes on the range $[0, 1]$ and correspondingly, K takes on the range $[0, \infty]$.

Here: $\tau_0 = 5.5$ nanosec

$$\frac{T_m}{\text{nanosec}} = 2.133 \quad \text{nanosec}$$