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.
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Abstract | This paper presents a channel model for UWB pulse systems operating at frequencies below 1 GHz.
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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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Release | The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.
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 $\eta_{\text{ant}}$. 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 integral over PSD for distances: 

$$d < (\text{Room}^2 + \text{Room}^2)^{1/2} \text{ m}$$

Where $\text{RoomX}$ and $\text{RoomY}$ 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 $h_1$ and $h_2$
- Average wall and floor reflection coefficient $\Gamma_m$
- Radiated power spectral density $EIRPsd(f)$
- Receiver antenna aperture $A_e$ and antenna efficiency $\eta_{ant}(f)$

![Figure 1. LOS components in a room of dimensions $RoomX$ by $RoomY$.](image)

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 signals 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 $\tau_m$
- 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 [Cassiolli 2002], and here is modeled by square root of distance $d/D$, scaled by the constant $\tau_0$. 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 $\tau_0$ 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 $\text{EIRPsd}(f)$
- Receiver antenna aperture $A_e$ and antenna efficiency $\eta_{\text{ant}}(f)$

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 $K_F$ 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


APPENDIX

Mathcad code for the 100 – 1,000 MHz Channel model Components
UWB Channel Model Components for use below 1 GHz
- Kai Siwiak


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 integral over PSD: $d < (\text{RoomX}^2 + \text{RoomY}^2)^{1/2} \text{ m}$
- Direct plus with $\Gamma^2$ power additional single reflection multipaths; $\Gamma^4$ 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 $d_t$
(2) Antenna heights $h_1$ and $h_2$
(2) Radiated power spectral density $\text{EIRPsd}(f)$
(3) Receiver antenna aperture $A_e$
(4) Multipath signal profile $S(t)$
(5) Average reflection coefficient $\Gamma_m$

Derived parameters include:
- RMS delay spread $\tau_{\text{rms}}$
- 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**

![Top view of signal paths inside a room.](image)

**Side view**

![Side view of signal paths inside a room.](image)

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 [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 and distance $D_t$
2. Mean interval between rays $T_m$ s
3. Fraction of energy in direct ray $K_f$
4. Radiated power spectral density $EIRPsd(f)$
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:


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

\[ d(x_1, x_2, y_1, y_2) := \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (h_2 - h_1)^2} \]  
\[ g_{nd}(x_1, x_2, y_1, y_2) := \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (h_2 + h_1)^2} \]

Separation distance projected on the ground is

\[ d_{gnd}(x_1, x_2, y_1, y_2) := \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \]

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

\[ r_1(x_1, x_2, y_1, y_2) := \sqrt{(x_2 - x_1)^2 + (y_2 + y_1)^2 + (h_2 - h_1)^2} \]  
\[ r_2(x_1, x_2, y_1, y_2) := \sqrt{(x_2 - x_1)^2 + (2(RoomY - y_2 - y_1)^2 + (h_2 - h_1)^2} \]  
\[ r_3(x_1, x_2, y_1, y_2) := \sqrt{(x_2 + x_1)^2 + (y_2 - y_1)^2 + (h_2 - h_1)^2} \]  
\[ r_4(x_1, x_2, y_1, y_2) := \sqrt{(2(RoomX - x_2 - x_1)^2 + (y_2 - y_1)^2 + (h_2 - h_1)^2} \]

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

\[ c_1(x_1, x_2, y_1, y_2) := \sqrt{(x_2 + x_1)^2 + (y_2 + y_1)^2 + (h_2 - h_1)^2} \]  
\[ c_2(x_1, x_2, y_1, y_2) := \sqrt{(x_2 + x_1 - 2(RoomX)^2 + (y_2 + y_1)^2 + (h_2 - h_1)^2} \]  
\[ c_3(x_1, x_2, y_1, y_2) := \sqrt{(x_2 + x_1 - 2(RoomX)^2 + (y_2 + y_1 - 2(RoomY)^2 + (h_2 - h_1)^2} \]  
\[ c_4(x_1, x_2, y_1, y_2) := \sqrt{(x_2 + x_1)^2 + (y_2 + y_1 - 2(RoomY)^2 + (h_2 - h_1)^2} \]
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. Nmd is the counter limit for index i and is set to several thousands to get statistically valid results. Coordinates (XR1i, YR1i) and (XR2i, YR2i) of the two direct path endpoints are selected.

Number of trials is:  \( N_{md} := 200000 \)  
\[ i := 0..N_{md} \]

\[ X1r_i := \text{md} (\text{Room}X - 2 \cdot \text{dt}) + \text{dt} \]
\[ Y1r_i := \text{md} (\text{Room}Y - 2 \cdot \text{dt}) + \text{dt} \]
\[ X2r_i := \text{md} (\text{Room}X - 2 \cdot \text{dt}) + \text{dt} \]
\[ Y2r_i := \text{md} (\text{Room}Y - 2 \cdot \text{dt}) + \text{dt} \]
\[ i := 0..N_{md} \]

Then the direct \( D_i \) distances and ground reflected \( G_r \) 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 \( eC1, eC2, eC3, eC4 \).

\[ D_i := d(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ D_g := d_g(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ R1_i := r1(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eR1_i := R1_i - D_i \]
\[ R2_i := r2(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eR2_i := R2_i - D_i \]
\[ R3_i := r3(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eR3_i := R3_i - D_i \]
\[ R4_i := r4(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eR4_i := R4_i - D_i \]
\[ G_r := gnd(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eG_i := G_r - D_i \]
\[ C1_i := c1(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eC1_i := C1_i - D_i \]
\[ C2_i := c2(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eC2_i := C2_i - D_i \]
\[ C3_i := c3(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eC3_i := C3_i - D_i \]
\[ C4_i := c4(X1r_i, X2r_i, Y1r_i, Y2r_i) \]
\[ eC4_i := C4_i - D_i \]
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 $\text{Gr}$. 

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].

\[ j := 0..9 \]

\[
\begin{array}{c|c|c}
\Gamma_j & \Gamma_j = & j = \\
0.3 & 0.3 & 0 \\
0.3 & 0.3 & 1 \\
0.3 & 0.3 & 2 \\
0.3 + 0.7 & 0.44 & 4 \\
0.3 + 2 \cdot \frac{7}{5} & 0.58 & 5 \\
0.3 + 3 \cdot \frac{7}{5} & 0.86 & 6 \\
0.3 + 4 \cdot \frac{7}{5} & 1 & 8 \\
1 & 1 & 9 \\
\end{array}
\]

\[ \Gamma_m := -\text{mean}(\Gamma) \]

\[
\Gamma_m = -0.58
\]

\[ 20 \cdot \log(\mid \Gamma_m \mid) = -4.731 \]  

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

\[ T_m := 1 + \Gamma_m \]

\[ 20 \cdot \log(T_m) = -7.535 \]

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:

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

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

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 antenna heights h1 and h2.

The rms delay spread $\tau_{\text{rms}}$ 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 projection of the vertical field vector on the receive antenna, via the ground reflection hence the ground component relative energy is approximately $\Gamma_{\text{rms}} = \Gamma_{\text{rms}}(1/Gr)^2(D/Gr)^4$. The delay spread is found from

$$\tau_{\text{rms}} = \sqrt{\frac{\text{tm}_i}{W_i} - \left(\frac{\text{tm}_i}{W_i}\right)^2}$$

The "total" energy in the room is $W_x$

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

$$\tau_{\text{rms}} := \sqrt{\text{tm}_i - \left(\frac{\text{tm}_i}{W_i}\right)^2} \quad \text{tm}_i := \text{mean}(\text{tm}_i)$$

(19)
Finally the rms delay spread $\tau_{\text{rms}}$ is found

$$\tau_{\text{rms}} := \frac{\text{tms}}{c} \quad (20)$$

and its value for the selected case is

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

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 $\tau_{\text{rms}}$ 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.

$$\text{scale} := 0.2$$

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

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

\[
\text{Delay}_i := \frac{eR_1 + eR_2 + eR_3 + eR_4 + eG_i + eC_1 + eC_2 + eC_3 + eC_4}{9}
\]

(21)

\[
D_{mn} := \frac{\text{mean}(\text{Delay})}{c} \quad D_{mn} = 2.878 \quad \text{m}
\]

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

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

\[
T_s := \frac{D_{mn}}{c} \quad T_s \cdot 10^9 = 9.6 \quad \text{nS}
\]

(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:

\[
H_{\text{LOS}}(t) := V_{fs}(d) \cdots + \Gamma^m \left( \frac{D_{g_i}}{G_{r_i}} \right) V_{fs}(d + eG) \cdot \delta \left( t - \frac{eG}{c} \right) \cdots + \Gamma^m \left( V_{fs}(d + eR_1) \cdot \delta \left( t - \frac{eR_1}{c} \right) \right) \cdots + \Gamma^m V_{fs}(d + eC_1) \cdot \delta \left( t - \frac{eC_1}{c} \right) \cdots
\]

(23)

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

\[
V_{fs}(d, f) := \sqrt{\frac{\text{EIRPsd}(f) \cdot \frac{1}{4\pi} \frac{\mu}{c}}{d}}
\]

(24)

where EIRPsd\((f)\) is the effective isotropically radiated power spectral density at frequency \( f \).
Figure 12. One particular realization of the LOS channel impulse amplitude response.
Figure 13. One particular realization of the LOS channel impulse energy response.
Plot multiple realizations of the model:

\[ x := 0.75 \quad \text{and} \quad p := 1 \]

\[
\begin{align*}
a_1 &= \left( \frac{D_i}{R_1} \cdot \Gamma_m \right)^p \\
a_2 &= \left( \frac{D_i}{R_2} \cdot \Gamma_m \right)^p \\
a_3 &= \left( \frac{D_i}{R_3} \cdot \Gamma_m \right)^p \\
a_4 &= \left( \frac{D_i}{R_4} \cdot \Gamma_m \right)^p \\
a_5 &= \left( \frac{D_i}{G_r} \cdot \Gamma_m \right)^p \\
a_6 &= \left( \frac{D_i}{C_1} \cdot \Gamma_m^2 \right)^p \\
a_7 &= \left( \frac{D_i}{C_2} \cdot \Gamma_m^2 \right)^p \\
a_8 &= \left( \frac{D_i}{C_3} \cdot \Gamma_m^2 \right)^p \\
a_9 &= \left( \frac{D_i}{C_4} \cdot \Gamma_m^2 \right)^p
\end{align*}
\]

Figure 14. Multiple realizations of the LOS channel impulse amplitude responses.
The receiver antenna aperture is:

\[
A_e := \frac{1.5}{4\pi} \int_{f_1}^{f_2} \left(1 - \frac{f}{f_2 - f_1}\right) \left(\frac{f}{c}\right)^2 \eta_{\text{ant}}(f) \cdot \text{EIRPsd}(f) \, df
\]

(25)

where:

- \(\eta_{\text{ant}}(f)\) is the antenna efficiency as a function of frequency
- EIRPsd(f) is the radiated effective isotropically radiated power spectral density

Thus the collected signal at the receiver is:

\[
S(t) := H_{\text{LOS}}(t) \sqrt{A_e}
\]

(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 \(h_2\)
3. Radiated power spectral density \(\text{EIRPsd}(f)\)
4. Receiver antenna aperture \(A_e\)
5. Multipath signal profile \(S(t)\)
6. Average reflection coefficient \(\Gamma_m\)

Derived parameters include:

- RMS delay spread \(\tau_{\text{rms}}\),
- 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 and \(T_s = 9.6 \times 10^{-9}\) 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.

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

(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.

To test the equations, let the initial delay spread equal $\tau_{rms}$ where

$$\tau_{rms} := 20 \text{ nanosec}$$

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 $2Ts/9$:

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

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

$$K_{max} := \lceil 10 \cdot \frac{\tau_{rms}}{Tm} \cdot R \rceil \quad K_{max} = 938 \quad k := 0..K_{max}$$

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

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

Channel coefficient $h$ is normally distributed with unity standard deviation:

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

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

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

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

Check the result

$$\sigma_2_k := \left(\sigma_k\right)^2 \quad \text{mean} \left(\sigma_2\right) K_{max} = 0.993 \quad (33)$$

$$h_k := \sigma_k \cdot h_k \quad h_2_k := \left(h_k\right)^2 \quad \text{mean}(h2) \cdot K_{max} = 1.222 \quad (34)$$
Thus the collected signal at the receiver is:

\[ S_N(t) := H_{\text{NLOS}}(t) \sqrt{\text{Ae}} \]  

(36)

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

Thus the collected signal at the receiver is:
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

\[ \tau_{\text{rms}}(d, D, \tau_0) := \tau_0 \sqrt{d \over D} \] (37)

A value for \( \tau_0 \) and D that approximately match channel models CM2, CM3, and CM4 in their appropriate distances [IEEE802 02/249] is:

\[ \tau_0 := 5.5 \quad \text{Dt} := 1 \] (38)

Thus

\[ \tau_{\text{rms}}(2, \text{Dt}, \tau_0) = 7.778 \]
\[ \tau_{\text{rms}}(7, \text{Dt}, \tau_0) = 14.552 \]
\[ \tau_{\text{rms}}(20, \text{Dt}, \tau_0) = 24.597 \]
\[ \tau_{\text{rms}}(50, \text{Dt}, \tau_0) = 38.891 \]
\[ \tau_{\text{rms}}(100, \text{Dt}, \tau_0) = 55 \]

The choice of trms 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 \( \text{SN}(t) \) 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 \( \tau_0 \) s multiplied by the square root of d/Dt
2. Mean interval between rays \( T_m \) s
3. Fraction of energy in direct ray \( K_f \)
4. Radiated power spectral density \( \text{EIRPsd}(f) \)
5. Receiver antenna aperture \( A_e \)
6. Multipath signal profile \( \text{SN}(t) \)

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, \( K_f \) takes on the range \([0, \infty]\).

Here: \[ \tau_0 = 5.5 \quad \text{nanosec} \]

\[ \frac{T_m}{\text{nanosec}} = 2.133 \quad \text{nanosec} \]