**IEEE 802.15**

**Wireless Specialty Networks**

|  |  |
| --- | --- |
| Project | IEEE 802.15 Working Group for Wireless Specialty Networks |
| Title | UWB Channel Models Document |
| Date Submitted | September 14th, 2022 |
| Source | |  |  | | --- | --- | | Takumi Kobayashi1,2, Marco Hernandez1,3, Ryuji Kohno1,2, Minsoo Kim21YRP-IAI, 2YNU, Japan, 3CWC Oulu Univ. Finland | Marco.Hernandez@ieee.org  Kohno@ynu.ac.jp  Kobayashi-Takumi-ch@ynu.ac.jp  Minsoo@minsookim.com | |
| Response | To call for contributions |
| Abstract | This document contains the channel models to evaluate proposals. |
| Purpose | For contributions to P802.15.6ma |
| Notice | This document has been prepared to assist the IEEE P802.15.6ma. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein. |

**Contributors**

|  |  |
| --- | --- |
| **Name & affiliation** | **Email** |
| Marco Hernandez, CWC, Oulu Univ. Finland, YRP-IAI Japan. | Marco.Hernandez@ieee.org |
| Ryuji Kohno, YRP-IAI, YNU, Japan | Kohno@ynu.ac.jp |
| Takumi Kobayashi, YRP-IAI, YNU, Japan | Kobayashi-Takumi-ch@ynu.ac.jp |
| Minsoo Kim, YRP-IAI, Japan. | Minsoo@minsookim.com |
| Kamran Sayrafian, NIST, USA. | kamran.sayrafian@nist.gov |
| Daisuke Anzai, Nagoya Institute of Technology, Japan. | Anzai@nitech.ac.jp |

**Revision history**

|  |  |  |
| --- | --- | --- |
| **Revision** | **Date** | **Notes** |
| 0 | 7/12/2022 | Document created |
| 1 | 7/14/2022 | Information has been added on Section 6.2. |
| 2 | 9/12/2022 | Updated |
| 3 | 9/14/2022 | S2.3 has been added. |
| 4 | 9/14/2022 | S4.1 has been removed. S6.1 and fig. 3 have been updated. |
|  |  |  |

Contents

[1. Introduction 1](#_Toc114137669)

[2. Scenarios for 15.6 revision 2](#_Toc114137670)

[2.1 Scenario 2.1 2](#_Toc114137671)

[2.2 Scenario 2.2 3](#_Toc114137672)

[2.3 Scenario 2.3 3](#_Toc114137673)

[2.4 Scenario 6.1 HBAN coordinator to HBAN coordinator 4](#_Toc114137674)

[2.5 Scenario 8.1 (passenger bus and HBANs) 6](#_Toc114137675)

[3. Antenna Effect 7](#_Toc114137676)

[3.1 Electrical antennas, such as dipole 7](#_Toc114137677)

[3.2 Magnetic antennas, such as loop 7](#_Toc114137678)

[4. Channel Characterization 8](#_Toc114137679)

[4.1 Electrical Properties of Body Tissues 8](#_Toc114137680)

[4.2 Model Types 8](#_Toc114137681)

[4.3 Fading 8](#_Toc114137682)

[4.3.1 Small-Scale Fading 8](#_Toc114137683)

[4.3.1.1 UWB Channel model 9](#_Toc114137684)

[4.3.1.2 Simulation methodology 9](#_Toc114137685)

[4.3.1.3 MatLab™ code 10](#_Toc114137686)

[4.3.2 Large-Scale Fading 12](#_Toc114137687)

[4.4 Path loss 12](#_Toc114137688)

[4.5 Shadowing 12](#_Toc114137689)

[5. Models and Scenarios 13](#_Toc114137690)

[5.1 Human BAN (HBAN) Channel models 13](#_Toc114137691)

[5.2 In-body 13](#_Toc114137692)

[5.2.1 Implant (upper body) to Body Surface CM2.1 (Scenario S2.1) for 3.1 – 10.6 GHz 13](#_Toc114137693)

[5.2.2 Implant (head) to Body Surface CM2.2 (Scenario S2.2) for 3.1 – 10.6 GHz 13](#_Toc114137694)

[5.2.3 Implant (head) to External CM2.3 (Scenario S2.3) for 3.1 – 10.6 GHz 15](#_Toc114137695)

[5.2.4 Implant (upper body) to External 15](#_Toc114137696)

[5.3 Body surface 15](#_Toc114137697)

[5.3.1 Body surface to body surface CM3 (Scenario S4 & S5) for 3.1-10.6 GHz 15](#_Toc114137698)

[5.3.2 Body surface to external CM4 (Scenario S6 & S7) for 3.1-10.6 GHz 17](#_Toc114137699)

[5.3.3 Dynamic channel model for body surface to body surface CM3 (Scenario S4 & S5) at 4.5 GHz 18](#_Toc114137700)

[5.4 Vehicle BAN (VBAN) channel models 24](#_Toc114137701)

[5.5 In Vehicle 24](#_Toc114137702)

[5.5.1 In vehicle to in vehicle 24](#_Toc114137703)

[5.5.1.1 Engine compartment to engine compartment (Scenario 8.X, CM X) 24](#_Toc114137704)

[5.5.1.2 In-vehicle to In-vehicle (Scenario 8, CM 8) 3.1 - 10.6GHz 25](#_Toc114137705)

[5.5.1.3 Cabin room to cabin room in omnibus (Scenario 8.1) 3.1 - 10.6GHz 26](#_Toc114137706)

[5.5.1.4 Cabin room to engine compartment [asymmetric] (Scenario 8.X, CM X) 3.1 – 10.6GHz 28](#_Toc114137707)

[5.5.1.5 Engine compartment to cabin room [symmetric] (Scenario 8.X CMx) 3.1 - 10.6GHz 29](#_Toc114137708)

[5.6 On vehicle 29](#_Toc114137709)

[5.6.1 On-vehicle to on-vehicle (Scenario 11, 12, CM11, 12) 29](#_Toc114137710)

[5.6.2 In-vehicle to on vehicle (Scenario 9, CM9) 3.1 – 10.6 GHz 30](#_Toc114137711)

[5.7 External 30](#_Toc114137712)

[5.7.1 In-vehicle to External (Scenario 10, CM 10) 3.1 – 10.6GHz 30](#_Toc114137713)

[5.7.2 On-vehicle to External with mobility consideration (Scenario 13 & 14 & 13) 31](#_Toc114137714)

[Annex A Bibliography 33](#_Toc114137715)

[Annex B (informative) Matlab code for IEEE802.15.4a UWB channel model 35](#_Toc114137716)

[Annex C (informative) MATLAB script for the IEEE 802.15.4a channel model 48](#_Toc114137717)

1. Introduction

The channel models used by IEEE Std 802.15.6-2012 Wireless Body Area Network (BAN) during the development of the Std cover use cases for medical and non-medical applications inside or on the surface of the human body. The frequency bands of operation are ISM bands used by narrowband and UWB implementations [1] .

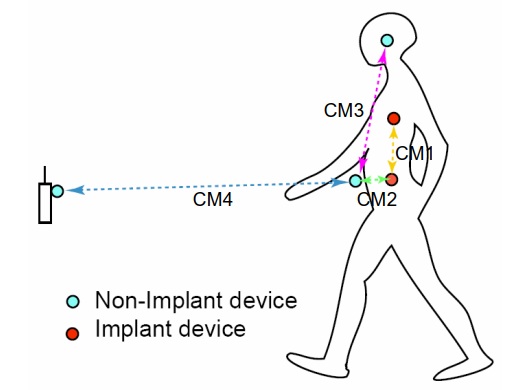
The channel models covered in this document are for the UWB band intended for body surfaces and vehicles. The channel models are aimed for the development of the PHY and MAC for the revision of IEEE 802.15.6 Std.

The channel model document of IEEE Std 802.15.6-2012 defined seven scenarios and four-channel models shown in Table 1 for illustration.

1. —Channel models used in IEEE Std 802.15.6-2012

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Description | Frequency Band | Channel Model |
| S1 | Implant to Implant | 402-405 MHz | CM1 |
| S2 | Implant to Body Surface | 402-405 MHz | CM2 |
| S3 | Implant to External | 402-405 MHz | CM2 |
| S4 | Body Surface to Body Surface (LOS) | 13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ | CM3 |
| S5 | Body Surface to Body Surface (NLOS) | 13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ | CM3 |
| S6 | Body Surface to External (LOS) | 900 MHz 2.4, 3.1-10.6 GHZ | CM4 |
| S7 | Body Surface to External (NLOS) | 900 MHz 2.4, 3.1-10.6 GHZ | CM4 |

Figure 1 illustrates such channel models.



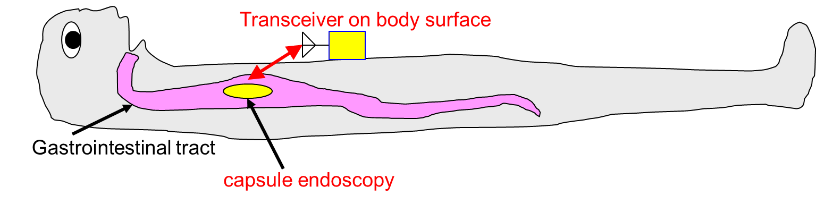
1. —Channel models for IEEE Std 802.15.6-2012
2. Scenarios for 15.6 revision
3. —15.6ma HBAN scenarios (notation in [1] ).

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Description | Frequency Band | Channel Model |
| S2 | Implant to Body Surface | 402-405 MHz | CM2 |
| S2.1 | Implant (upper body) to Body Surface | 3.1-10.6 GHz | CM2.1 |
| S2.2 | Implant (head) to Body Surface | 3.1-10.6 GHz | CM2.2 |
| S2.3 | Implant (head) to external | 3.1-10.6 GHz | CM2.3 |
| S3 | Implant (upper body) to External | 402-405 MHz  3.1-10.6GHz | CM3 |
| S4 | Body Surface to Body Surface (LOS) | 400, 600, 900 MHz 2.4, 3.1-10.6 GHz | CM3 |
| S5 | Body Surface to Body Surface (NLOS) | 2.4, 3.1-10.6 GHz | CM3 |
| S6 | Body Surface to External (LOS) | , 3.1-10.6 GHz | CM4 |
| S6.1 | BAN coordinator to BAN coordinator | 3.1-10.6 GHz | CM4.1 |
| S7 | Body Surface to External (NLOS) | , 3.1-10.6 GHz | CM4 |

The present document describes the new channel models for scenarios S2.1, S2.2, S4.1 and S6.1.

* 1. Scenario 2.1

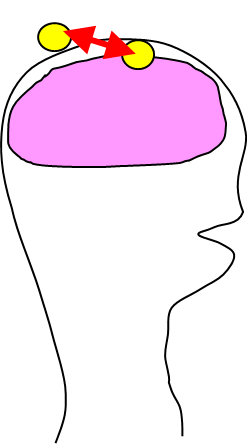
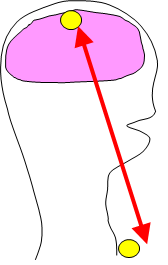
The new scenario S2.1 is for the implant (upper body) to body surface on the UWB band for applications such as capsule endoscopy.

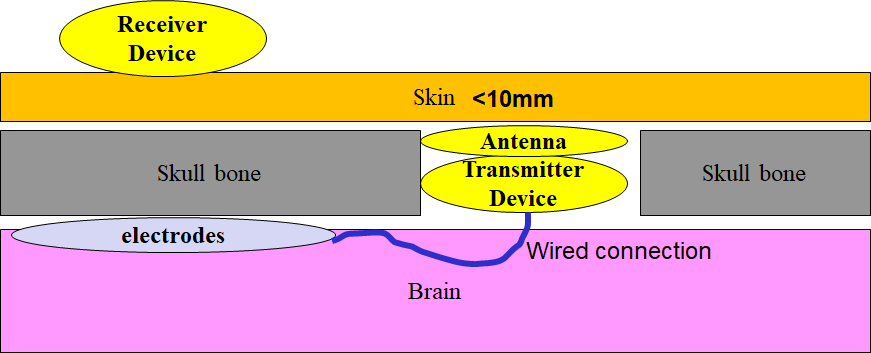


1. —Scenario 2.1: Capsule endoscopy application
   1. Scenario 2.2

The new scenario S2.2 is for the implant (head) to the body surface on the UWB band for applications such as the brain-computer interface (BCI). Note the transmitting antenna is integrated into the transmitter device over a titanium plaque that replaces the skull bone. In that way, the embedded transmitter is under the skin to avoid infection. Electrodes are implanted on the brain and join by a small cable to the transmitter device. The receiver may be located around the head (headband or other wearable) or torso.

Receiver could be located on the head by using head gear or something wearable to make easy to implementation of the antennas.

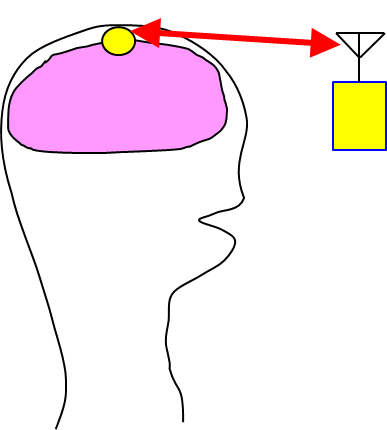
 



1. —Scenario 2.2: implant (head) in-body to body surface.
   1. Scenario 2.3

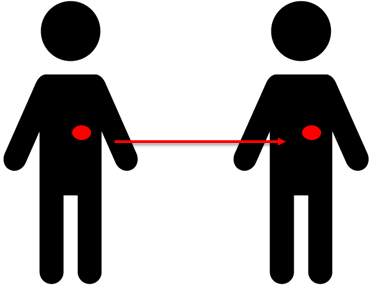
The new scenario S2.3 is for the implant (head) to external on the UWB band for applications such as the brain-computer interface (BCI). Note the transmitting antenna is integrated into the transmitter device over a titanium plaque. In that way, the embedded transmitter is under the skin to avoid infection.

The receiver may be located within a range of 2m in LOS.



1. —Scenario 2.3: implant (head) to external.
   1. Scenario 6.1 HBAN coordinator to HBAN coordinator

The new scenario 6.1 covers HBAN coordinator to HBAN coordinator.

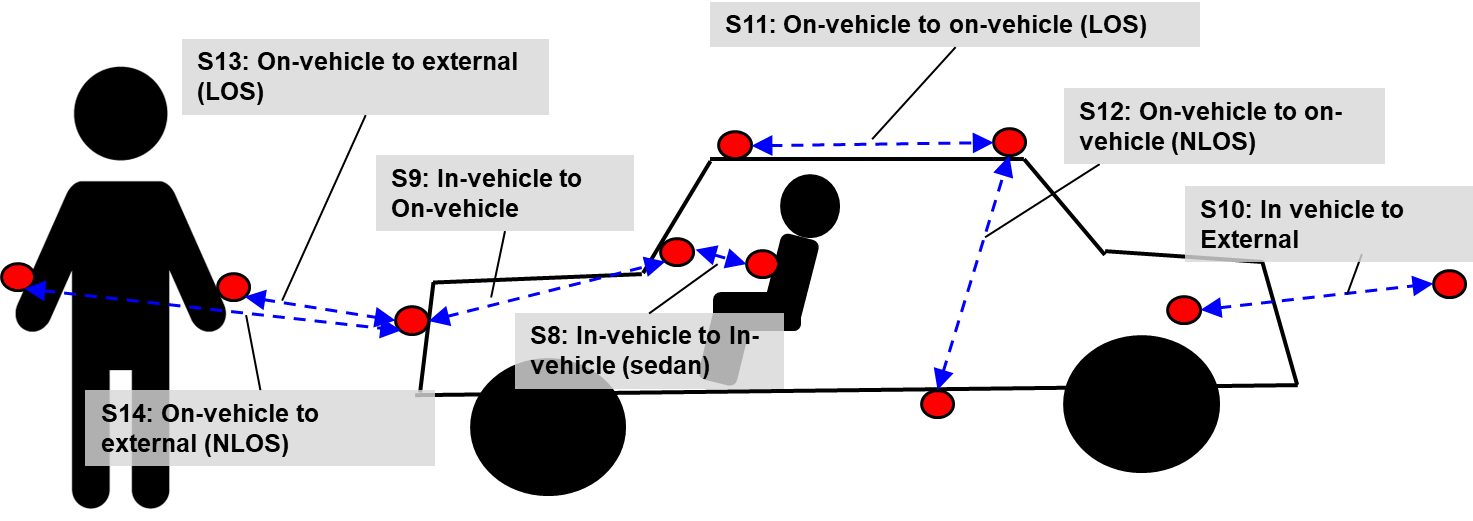


1. —Scenario 6.1: HBAN coordinator to HBAN coordinator.

NOTE: CM4 supports the scenario HBAN coordinator to VBAN coordinator

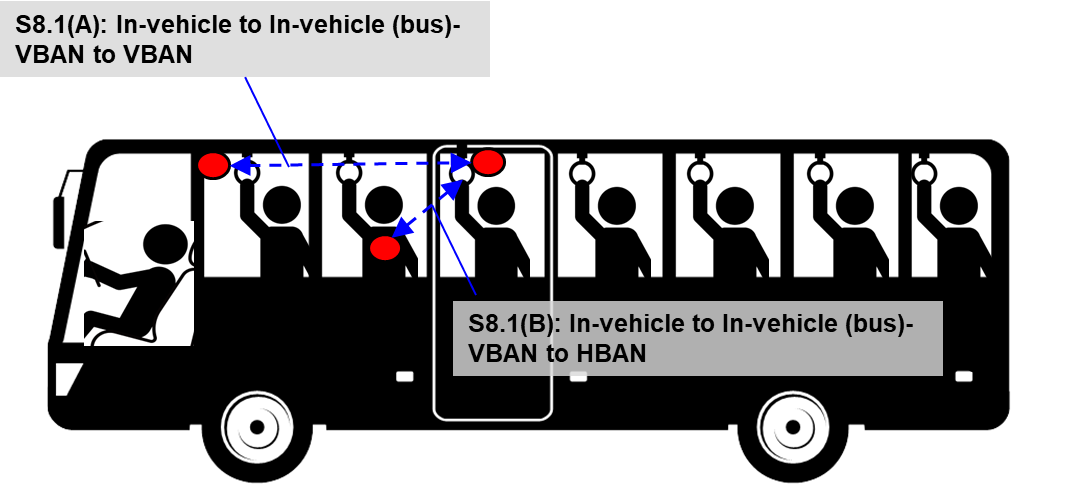
1. —15.6 VBAN scenarios

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Description | Frequency Band | Channel Model |
| S8 | In-vehicle to In-vehicle (sedan) | 2.4, 3.1-10.6 GHZ | CM8 |
| S8.1 | In-vehicle to In-vehicle (passenger bus) | 2.4, 3.1-10.6 GHZ | CM8.1 |
| S9 | In-vehicle to On-vehicle | 2.4, 3.1-10.6 GHZ | CM9 |
| S10 | In vehicle to External | 2.4, 3.1-10.6 GHZ | CM10 |
| S11 | On-vehicle to on-vehicle (LOS) | 2.4, 3.1-10.6 GHZ | CM11 |
| S12 | On-vehicle to on-vehicle  (NLOS) | 2.4, 3.1-10.6 GHZ | CM12 |
| S13 | On-vehicle to external (LOS) | 2.4, 3.1-10.6 GHZ | CM13 |
| S14 | On-vehicle to external (NLOS) | 2.4, 3.1-10.6 GHZ | CM14 |



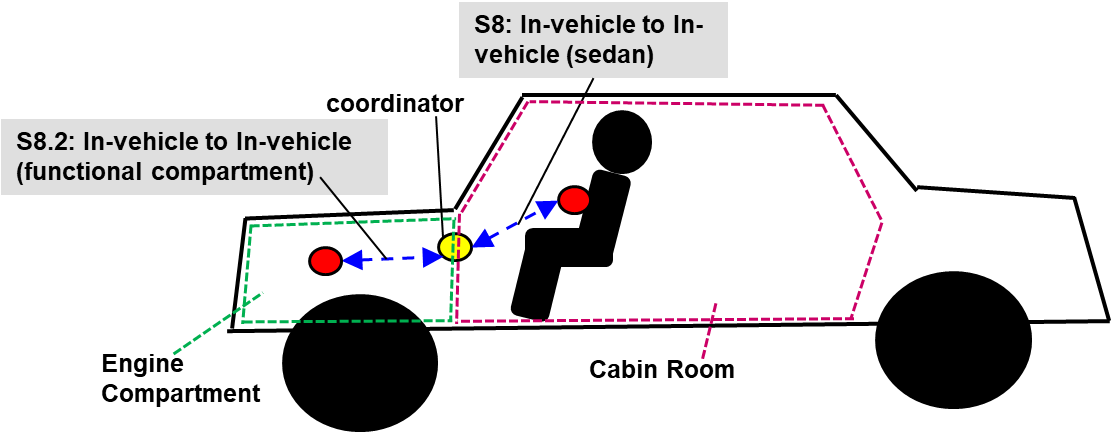
1. —Channel models and scenarios for VBAN

Figure 6 shows an overview of models of VBAN applications.



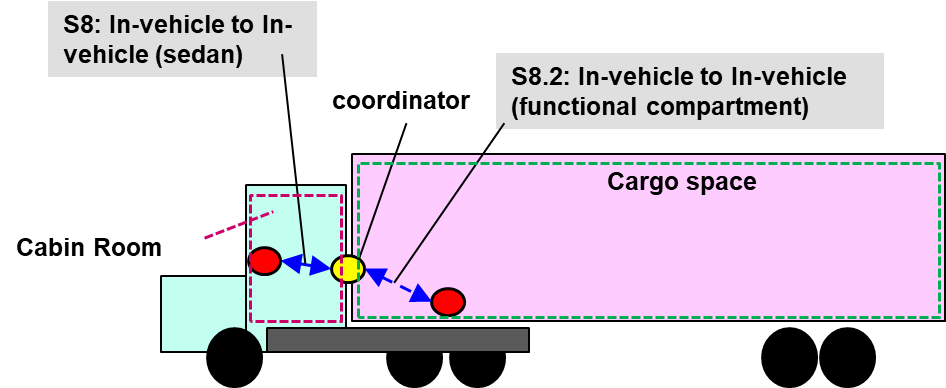
1. —Scenario S8.1: In-vehicle to In-vehicle (bus)

Figure 7 shows scenario S8.1 which is targeting a use case in passenger bus. There are two scenarios S8.1(A) and S8.1(B). Scenario S8.1(A) illustrates the scenario VBAN to VBAN, while S8.1(B) illustrates the scenario of VBAN to HBAN.



1. —Scenario S8.2: In-vehicle to In-vehicle (functional compartment)

Figure 8 shows scenario S8.2, which can be used for the analysis of wireless connection between cabin’s room and the other functional compartments such as the engine compartment and cargo space as shown in Figure 9.



1. —Scenario S8.2: In-vehicle to In-vehicle (functional compartment) ; Cargo vehicle use case

In order to reduce disconnection between odevices in the cabin’s room and functional space room, a coordinator may be placed in between these two the cabin’s room and cargo space.

* 1. Scenario 8.1 (passenger bus and HBANs)

1. Antenna Effect

An antenna placed on the surface or inside a body will be heavily influenced by its surroundings [2] . The consequent changes in antenna pattern and other characteristics need to be understood and accounted for during any propagation measurement campaign.

The form factor of an antenna will be highly dependent on the requirements of the application. For MICS applications, for example, a circular antenna may be suitable for a pacemaker implant, while a helix antenna may be required for a stent or urinary implant. The form factor will affect the performance of the antenna and, the antenna performance will be very important to the overall system performance. Therefore, an antenna which has been designed with respect to the body tissues (or considered the effect of human body) shall be used for the channel model measurements [3] .

* 1. Electrical antennas, such as dipole

Electrical antenna typically generates large components of E-field normal to the tissue interface, which overheat the fat tissue. This is because boundary conditions require the normal E-field at the interface to be discontinuous by the ratio of the permittivity, and since fat has a lower permittivity than muscle, the E-field in the fat tissue is higher.

* 1. Magnetic antennas, such as loop

Magnetic antenna produces an E-field mostly tangential to the tissue interface, which seem not to couple as strongly to the body as electrical antennas. Therefore, it does not overheat the fat.

There are antennas same as helical-coil, which is similar to a magnetic antenna in some respect, but its heating characteristics appear to be more like an electrical antenna. The strong E-field generated between the turns of coil is mainly responsible for tissue heating

It should be noted that SAR in the near field of the transmitting antenna depends mainly on the H-field; however, SAR in the far field of the transmitting antenna depends mainly on the E-field.

1. Channel Characterization
   1. Electrical Properties of Body Tissues

The human body is not an ideal medium for radio frequency wave transmission. It is partially conductive and consists of materials of different dielectric constants, thickness, and characteristic impedance. Therefore depending on the frequency of operation, the human body can lead to high losses caused by power absorption, central frequency shift, and radiation pattern destruction. The absorption effects vary in magnitude with both frequency of applied field and the characteristics of the tissue [[4] [5] [6] [7] ].

* 1. Model Types

In all cases, two types of models may be generated:

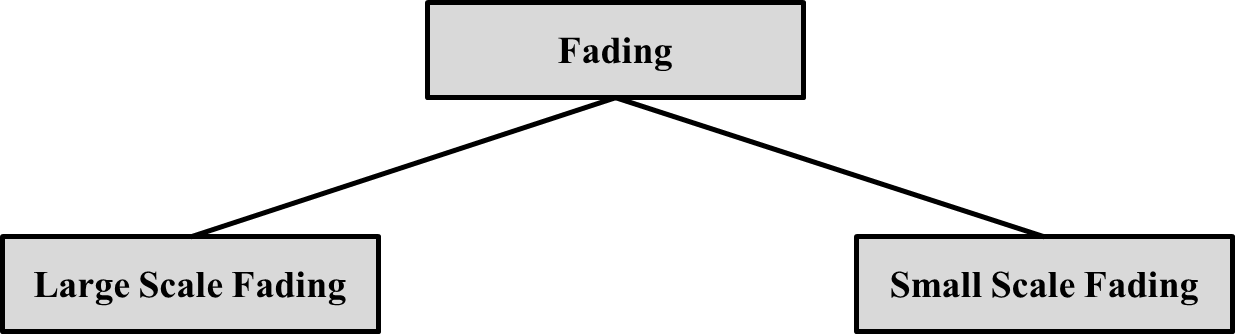
* A theoretical or mathematical model including numerical simulation based modeling.
* An empirical model

A theoretical model may be traceable back to the fundamental principles of electromagnetic propagation and will permit precise modeling of a specific situation at radio link level. It is intended for detailed exploration of, for example, the influence of body structures on antenna patterns. It will require a detailed description of the propagation environment and is therefore probably not suitable for modeling of macro environments.

An empirical model may be traceable to an agreed set of propagation measurements and is intended to provide a convenient basis for statistical modeling of the channel. Compared to the theoretical model, the empirical model will use a greatly simplified description of the environment and, although statistically accurate at network level, will not be precise at link level. Appropriate efforts could be made to ensure that the two sets of models are consistent with each other.

* 1. Fading

In the body area network communications, propagation paths can experience fading due to different reasons, such as energy absorption, reflection, diffraction, shadowing by body, and body posture. The other possible reason for fading is multipath due to the environment around the body. Fading can be categorized into two categories; small scale and large-scale fading.



Small-Scale Fading

Small scale fading refers to the rapid changes of the amplitude and phase of the received signal within a small local area due to small changes in location of the on-body device or body positions, in a given short period of time. The small-scale fading can be further divided into flat fading and frequency selective fading.

Averaging the attenuation between each antenna position on the body and each antenna locationin the room will remove the effect of small scale fading due to small changes in the body position.

* + - * 1. UWB Channel model

The UWB channel impulse responses are taken from the channel models document of former IEEE802.15.4a TG. Scenarios, bandwidths and central frequencies are similar to the ones targeted for IEEE802.15.8 TG. The MatLab code is attach in Annex A.

* + - * 1. Simulation methodology

The power delay profiles are taken from the extended ITU channel models described in [8] with Doppler spectrum characterized by the Jakes spectrum shape and maximum Doppler frequency shift, as suggested in [9] . The spatial correlation is described in [8] . Figure 10 shows the schematic flow for simulation of Kronecker model, already implemented in Matlab Simulink. In Figure 11, the correlated MIMO channel simulation is delineated.



1. — Schematic flow of simulation for the Kronecker model.

where is the power of the channel coefficient of *q*th tap resulting between the coupling of *i*th antenna at transmitter to *j*th antenna at receiver.



1. — Channel simulation methodology.
   * + - 1. MatLab™ code

The following scripts were written in MatLabR2011 and the Communications Toolbox. It exploits the new interface between Matlab and Simulink for optimizing speed.

% %

% function [H] = ExtendedITU\_MIMOChannel(model,correlation, %

% configuration,fd,fs) %

% %

% Return object for FIR taps of Extended ITU MIMO channel models %

% %

% INPUT PARAMETERS: %

% model = Extended ITU channel model %

% correlation = Spatial correlation level %

% configuration = Antenna configuration %

% fd = Maximum Doppler shift in Hz %

% fs = Simulation sampling frequency in Hz %

% %

% OUTPUT VALUE: %

% H = complex channel taps %

% %

% Author: Marco Hernandez, v1.0 %

% \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\* %

function [H] = ExtendedITU\_MIMOChannel(model,correlation,configuration,fd,fs)

switch model

case 'pedestrian'

% vector of path delays in sec

tau = [0 30 70 80 110 190 410]\*1e-9;

% vector of average path power gains in dB

pdb = [0 -1 -2 -3 -8 -17.2 -20.8];

case 'vehicular'

tau=[0 30 150 310 370 710 1090 1730 2510]\*1e-9;

pdb=[0 -1.5 -1.4 -3.6 -0.6 -9.1 -7 -12 -16.9];

case 'urban'

tau=[0 50 120 200 230 500 1600 2300 5000]\*1e-9;

pdb=[-1 -1 -1 0 0 0 -3 -5 -7];

otherwise

error('Model not implemented.');

end

switch correlation

case 'low'

a=0; b=0;

case 'medium'

a=0.3; b=0.9;

case 'high'

a=0.9; b=0.9;

otherwise

error('Spatial correlation profile not implemented.');

end

switch configuration

case '1x2'

Nt=1; Nr=2; Rt=1; Rr=[1 b;b 1];

case '2x1'

Nt=2; Nr=1; Rt=[1 a;a 1]; Rr=1;

case '2x2'

Nt=2; Nr=2; Rt=[1 a;a 1]; Rr=[1 b;b 1];

case '4x2'

Nt=4; Nr=2; Rt=[1 a^(1/9) a^(4/9) a;a^(1/9) 1 a^(1/9) a^(4/9);a^(4/9) a^(1/9) 1 a^(1/9);a a^(4/9) a^(1/9) 1];

Rr=[1 b;b 1];

case '2x4'

Nt=2; Nr=4; Rt=[1 a;a 1];

Rr=[1 b^(1/9) b^(4/9) b;b^(1/9) 1 b^(1/9) b^(4/9);b^(4/9) b^(1/9) 1 b^(1/9);b b^(4/9) b^(1/9) 1];

case '4x4'

Nt=4; Nr=4; Rt=[1 a^(1/9) a^(4/9) a;a^(1/9) 1 a^(1/9) a^(4/9);a^(4/9) a^(1/9) 1 a^(1/9);a a^(4/9) a^(1/9) 1];

Rr=[1 b^(1/9) b^(4/9) b;b^(1/9) 1 b^(1/9) b^(4/9);b^(4/9) b^(1/9) 1 b^(1/9);b b^(4/9) b^(1/9) 1];

otherwise

error('Antenna configuration not implemented.');

end

% Object MIMO multipath fading channel

H=comm.MIMOChannel(...

'SampleRate', fs,...

'PathDelays', tau,...

'AveragePathGains', pdb,...

'MaximumDopplerShift', fd,...

'DopplerSpectrum', doppler.jakes,...

'NumTransmitAntennas', Nt,...

'NumReceiveAntennas', Nr,...

'TransmitCorrelationMatrix', Rt,...

'ReceiveCorrelationMatrix', Rr,...

'FadingDistribution', 'Rayleigh',...

'RandomStream', 'mt19937ar with seed',...

'Seed', 99,...

'NormalizePathGains', true,...

'NormalizeChannelOutputs', true,...

'PathGainsOutputPort', false );

end

Large-Scale Fading

Large scale fading refers to the fading due to motion over large areas; this is referring to the distance between antenna positions on the body and external node (home, office, or hospital).

* 1. Path loss

Unlike traditional wireless communications, the path loss for body area network system (on body applications), is both distance and frequency dependent. The frequency dependence of bod tissues shall be considered. The path loss model in dB between the transmitting and the receiving antennas as a function of the distance d based on the Friis formula in free space is described by [[10] [11] ]:



where *PL0* is the path loss at a reference distance d0, and n is the path-loss exponent.

The path loss near the antenna depends on the separation between the antenna and the body due

to antenna mismatch. This mismatch indicates that a body-aware antenna design could improve

system performance.

* 1. Shadowing

Due to the variation in the environment surrounding of body or even movement of the body parts, path loss will be different from the mean value for a given distance as shown in equation (1). This phenomenon is called shadowing, and it reflects the path loss variation around the mean. The shadowing should be considered for stationary and non-stationary position of body.

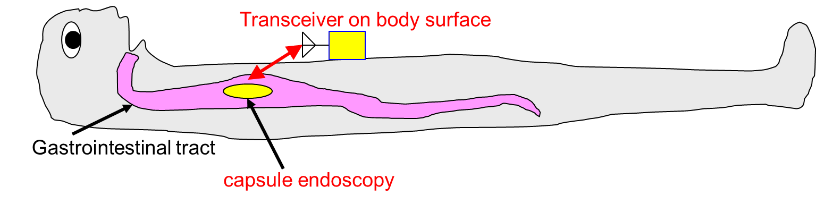
When considering shadowing, the total path loss PL can be expressed by:



where *PL(d)* is expressed by the Equation (1) and *S* represents the shadowing component.

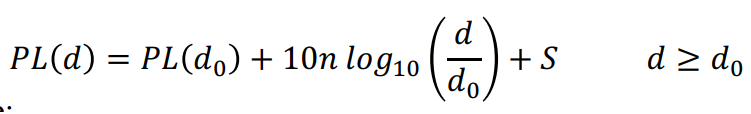
1. Models and Scenarios
   1. Human BAN (HBAN) Channel models
   2. In-body
      1. Implant (upper body) to Body Surface CM2.1 (Scenario S2.1) for 3.1 – 10.6 GHz

Scenario S2.1 is a model for the implant to the body surface on the UWB band for specific applications such as capsule endoscopy. This model is developed based on doc.# P.802.15-22-0401-00-6a [12] .



1. —Scenario 2.1: Capsule endoscopy application

Path Loss (PL) versus distance (d) can be represented by:

……….

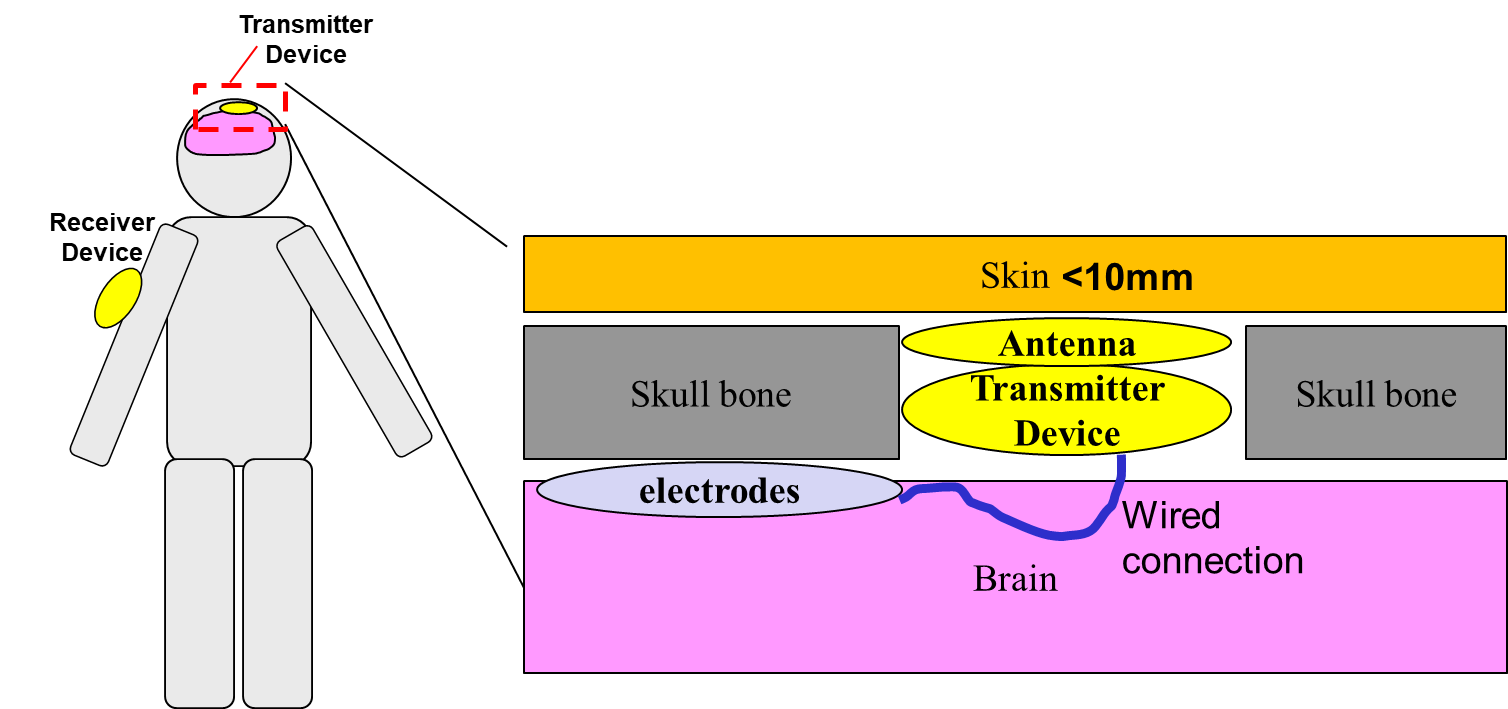
Where, *d*0 is a reference distance, *n* is the pathloss exponent, *S* is the random scatter around the regression line with Normal Distribution with standard deviation *σ*s

1. 6.2.2 Implant to Body Surface CM2.1 for 3.1 – 10.6 GHz parameters

|  |  |  |  |
| --- | --- | --- | --- |
| Implant to body surface | *PL(d0) (dB)* | *n* | *σs (dB)* |
|  | 51.9 | 8.14 | 18.19 |

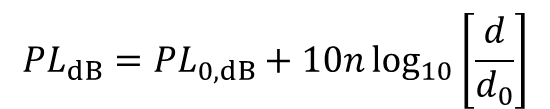
* + 1. Implant (head) to Body Surface CM2.2 (Scenario S2.2) for 3.1 – 10.6 GHz

Scenario S2.2 is for the implant to the body surface on the UWB band for specific applications such as the brain-computer interface (BCI). Note the transmitting antenna is integrated into the transmitter device over a titanium plaque that replaces the skull bone. In that way, the embedded transmitter is under the skin to avoid infection.



1. – Scenario S2.2 implant (head) to body surface

Path loss model is defined as

.

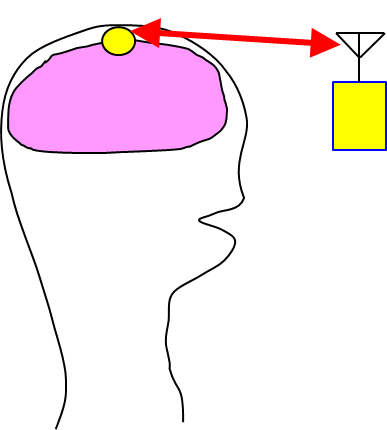
Path loss parameters are simulated and provided in [13] ,[14] ,[15] ,[16] ,[17] as follows.

1. 6.2.2 Implant (head) to Body Surface CM2.2 for 3.1 – 10.6 GHz parameters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Transmitting antenna | Received components | *d*0 [m] | *PL0* (dB) | *n* |
| *x* | *x* | 0.48 | *109.8* | *2.22* |
| *y* | *100.8* | *3.12* |
| *z* | *118.5* | *1.23* |
| *y* | *x* | *103.9* | *0.85* |
| *y* | *85.3* | *3.02* |
| *z* | *101.4* | *2.16* |
| *z* | *x* | *87.2* | *0.91* |
| *y* | 68.2 | 3.27 |
| *z* | 84.7 | 2.23 |

Implant (head) to External CM2.3 (Scenario S2.3) for 3.1 – 10.6 GHz

Scenario S2.3 is for the implant (head) to external on the UWB band for applications such as the brain-computer interface (BCI). Note the transmitting antenna is integrated into the transmitter device over a titanium plaque. In that way, the embedded transmitter is under the skin to avoid infection.



1. —Scenario 2.3: implant (head) to external.

Implant (upper body) to External

[TBD]

* 1. Body surface

Body surface to body surface CM3 (Scenario S4 & S5) for 3.1-10.6 GHz

The following path loss model is based on measurements that cover frequencies of 3.1-10.6 GHz. Measurement set up, derivation and data analysis can be found in [18] . The table below summarizes the model and corresponding parameters.

1. Parameters of the path loss model for CM3 (S4 & S5)

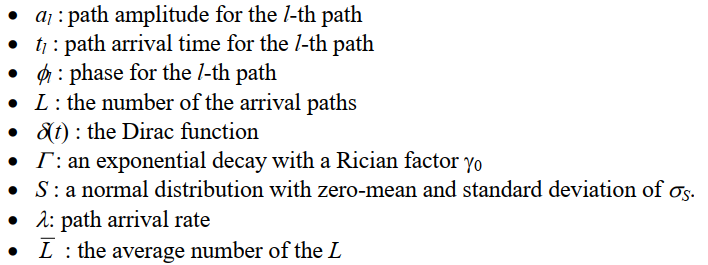
|  |  |  |
| --- | --- | --- |
|  | Hospital Room | Anechoic Chamber |
| Path loss model | *PL(d)*[dB] = *a ⬝* log10(*d*) + *b* + *N* | |
| *a* | 19.2 | 34.1 |
| *b* | 3.38 | -31.4 |
| σ*N* | 4.40 | 4.85 |

* *a* and *b* : Coefficients of linear fitting
* *d* : Tx -Rx distance in mm
* *N* : Normally distributed variable with zero mean and standard deviation σ*N*

A power delay profile (PDP) model for 3.1 – 10.6 GHz is also given in [18] . The table below summarizes this model and corresponding parameter.

1. Parameters of the PDP model for CM3 (S4 & S5)

|  |  |  |
| --- | --- | --- |
| PDP Model | φ*l* is modeld by a uinform distribution over [0,2π) | |
| *al* | γ0 | -4.60 dB |
| Γ | 59.7 |
| σs | 5.02 dB |
| *tl* | 1/λ | 1.85 ns |
| *L* |  | 38.1 |

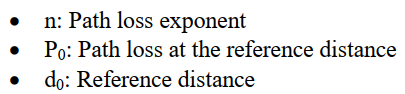


Option 2

The following path loss model is based on measurements that cover frequencies of 3.1-10.6 GHz. Measurement set up, derivation and data analysis can be found in [19] . The table below summarizes the corresponding parameters.

1. Parameters of the path loss model for CM3 (S4 & S5) (Option 2)

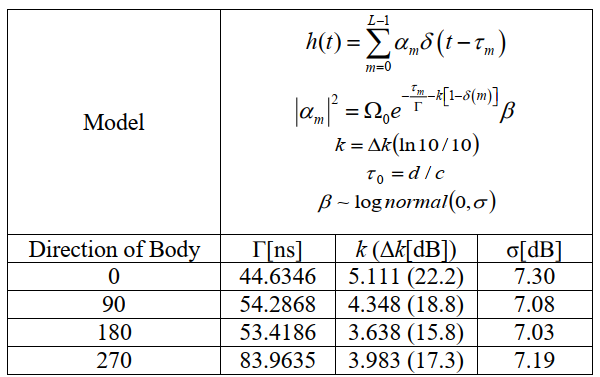
|  |  |  |
| --- | --- | --- |
| Path loss model |  | |
| Around torso | | |
| Antenna separation from body surface | 0 mm | 5 mm |
| P0 [dB] | 56.1 | 48.4 |
| d0 [m] | 0.1 | 0.1 |
| n | 5.8 | 5.9 |
|  |  |  |
| Along torso | | |
| Antenna separation from body surface | 0 mm | 5 mm |
| P0 [dB] | 56.5 | 44.6 |
| d0 [m] | 0.1 | 0.1 |

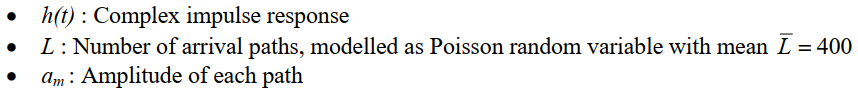
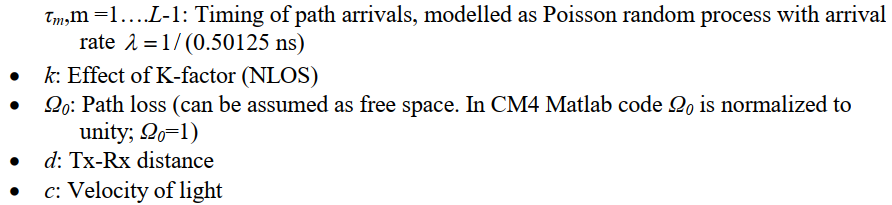


Body surface to external CM4 (Scenario S6 & S7) for 3.1-10.6 GHz

Measurement for the UWB frequency band of 3.1-10.6 GHz has been performed in [20] . On body antenna characteristics were measured in anechoic chamber, while channel measurements were done in office environment. For this measurement, the Tx antenna is fixed near to wall, while the Rx antenna (placed on body) positions were changed in office area. The effect of ground is considered in measurements. All data were averaged for statically analysis; therefore, the detail data of each measurement is not provided. The Further detail on set-up, derivation and data analysis can be found in [20] . The following figures summarize the delay profile of front, side, and backside of body while the Tx antenna is in the front of body.

1. Parameters of the path loss model for CM4 (Scenario S6 & S7) for 3.1-10.6 GHz



Dynamic channel model for body surface to body surface CM3 (Scenario S4 & S5) at 4.5 GHz

A real time channel measurements by use of channel sounder has been performed in [21] . The channel measurements were carried out in an anechoic chamber with center frequency of 4.5 GHz and bandwidth of 120 MHz. Details of the measurement set up, derivation and data analysis can be found in [21] . The measurements are focusing on the fading effect due to movements of the human body, therefore conducted in an anechoic chamber, where the multipath from the surrounding objects are negligible.

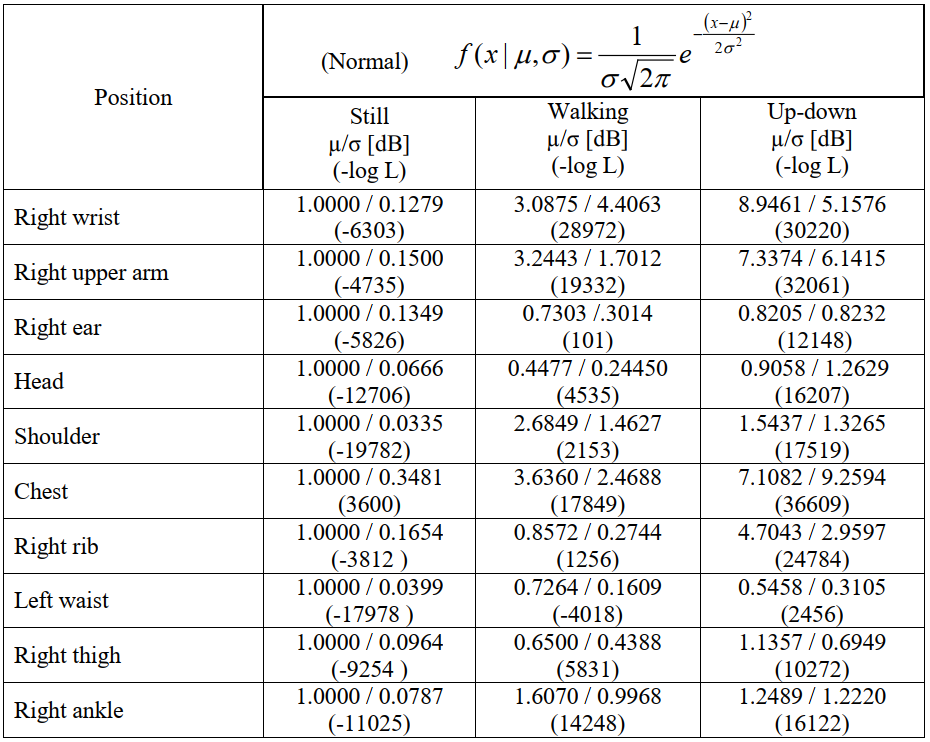
The transmitter antenna was fixed on around navel. The table below summarize the position of receiving antennas and distance between Tx and Rx antennas.

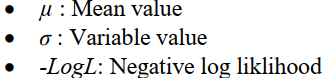
1. Summary of the position of receiving antennas and distance between Tx and Rx antennas for CM3 (Scenario S4 & S5) at 4.5 GHz

|  |  |
| --- | --- |
| Position | Distance [mm] |
| A Right wrist | 440 ~ 525 |
| B Right upper arm | 360 |
| C Left ear | 650 |
| D Head | 710 |
| E Shoulder | 310 |
| F Chest | 230 |
| G Right rib | 183 |
| H Left waist | 140 |
| I Thigh | 340 |
| J Ankle | 815 ~ 940 |

To provide a statistical model, the probability distribution functions such as normal, log-normal and Weibull distributions have been tried to fill the measurement results. The tables below summarize the normal, log-normal and Weibull distributions.

1. Summary of the normal distributions parameter for CM3 (Scenario S4 & S5) at 4.5 GHz



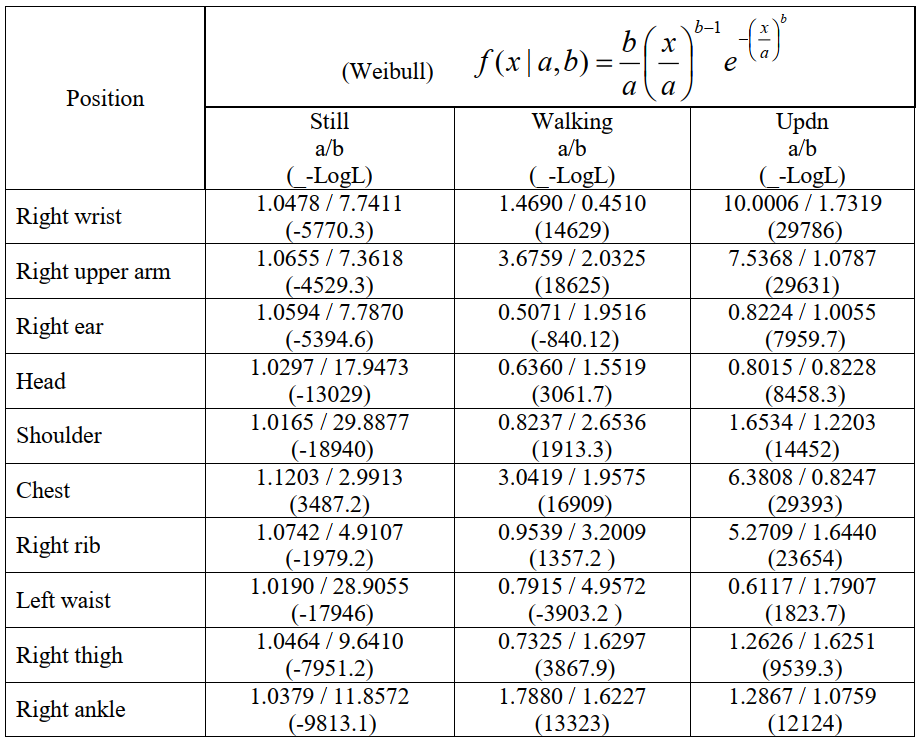


1. Summary of the log-normal distribution parameters for CM3 (Scenario S4 & S5) at 4.5 GHz



* μ: Mean value
* σ: Variable value
* -*LogL*: Negative log loklihood

1. Summary of the Weibull distribution parameters for CM3 (Scenario S4 & S5) at 4.5 GHz



* *a* : Scale factor
* *b*: Shape factor
* -*LogL*: Negative log loklihood

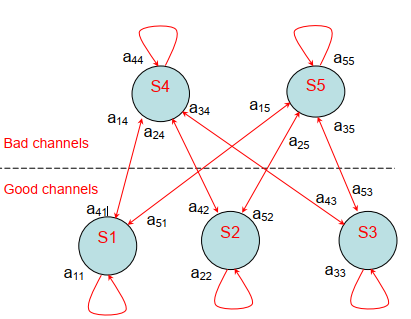
The below table summarize the best fitting distributions for dynamic channel at 4.5 GHz.

1. Summary of the best fitting distributions for dynamic channel parameters for CM3 (Scenario S4 & S5) at 4.5 GHz

|  |  |  |  |
| --- | --- | --- | --- |
| Position | Still | Walking | Up-down |
| Right wrist | Normal | Weibull | Weibull |
| Right upper arm | Log-normal | Weibull | Weibull |
| Right ear | Normal | Log-normal | Weibull |
| Head | weibull | Log-normal | Log-normal |
| Shoulder | Log-normal | Weibull | Weibull |
| Chest | Log-normal | Log-normal | Weibull |
| Right rib | Log-normal | Log-normal | Weibull |
| Left waist | Normal | Log-normal | Weibull |
| Right thigh | Log-normal | Log-normal | Weibull |
| Right ankle | Log-normal | Weibull | Weibull |

* Normal distribution seems to fit the still posture best, but it can be seen that fittings with any distributions have large from the PDFs.
* Log-normal distribution shows good match in cases of still postures and small movements such as walking posture in case of head , right ear, chest, right rib, left waist, right thigh, and stand up/down posture in case of head.
* Weibull distribution can represent much better large movement behaviors such as walking posture in case of right wrist, right upper arm, shoulder, right ankle, and all stand up/down postures except for head.

Based on statistical analysis of fading duration a 5-state Fritchman model for dynamic on-body channels, as shown in the below Figure, has been used to classifies channel states according to the dwelling time (ϴ) in different channel qualities to quantitatively describe the time-varying property of on-body channels.



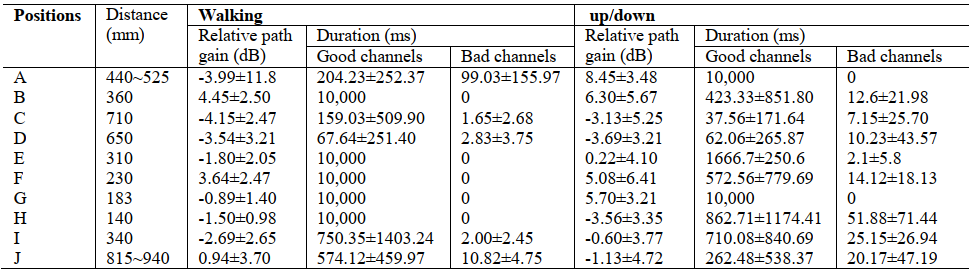
1. Five-state Fritchman model for dynamic on-body channels

The five-state Fritchman model for describing the burst behaviors of on-body channels are:

* S1: unstable error-free state, good channels which last less than 20 ms;
* S2: semi-constant error-free state, good channel which are over 20 ms and less than 400
* ms;
* S3: constant error-free state, good channel which are over 400 ms;
* S4: unstable error state, bad channel which last less than 20 ms, and
* S5: semi-constant error state, bad channel which are less than 400 ms.

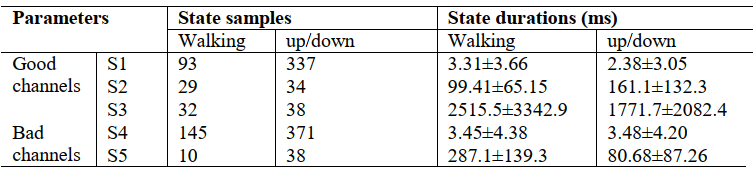
The statistical parameters for the on-body dynamic channel at ϴ=-10dB for different locations are;

1. statistical parameters for the on-body dynamic channel



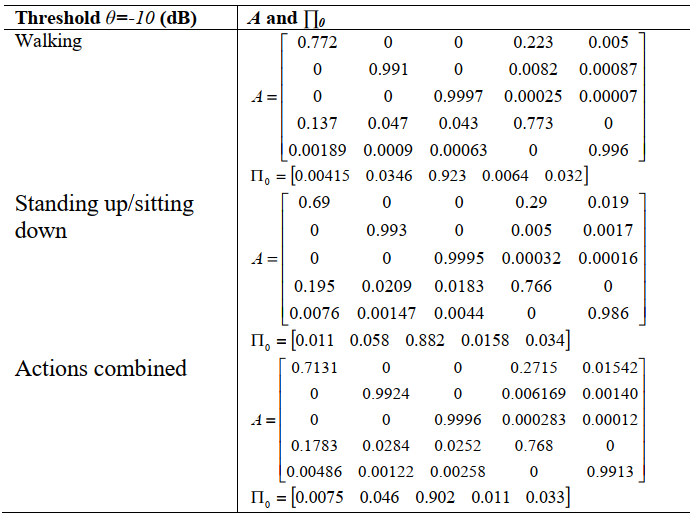
The statistical parameters for the on-body dynamic channel at ϴ=-10dB in different states are

1. — statistical parameters for the on-body dynamic channel



Parameters of the 5-state Fritchman model for different action scenarios are

1. Parameters of the five-state Fritchman model for different action scenarios



* 1. Vehicle BAN (VBAN) channel models

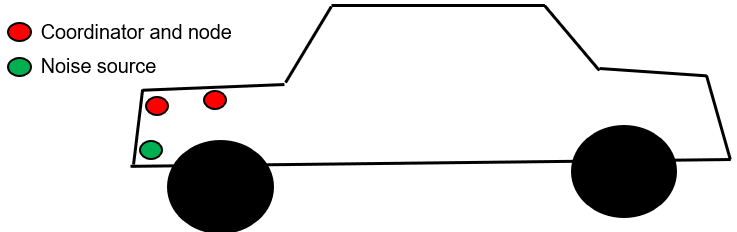
VBAN channel models are defined as four cases; in-vehicle to in-vehicle, on-vehicle to on-vehicle and on-vehicle to surrounding vehicle cases.

The considered channel models are based on the IEEE 802.15.4a channel model document [22] .

* 1. In Vehicle

In vehicle to in vehicle

* + - * 1. Engine compartment to engine compartment (Scenario 8.X, CM X)



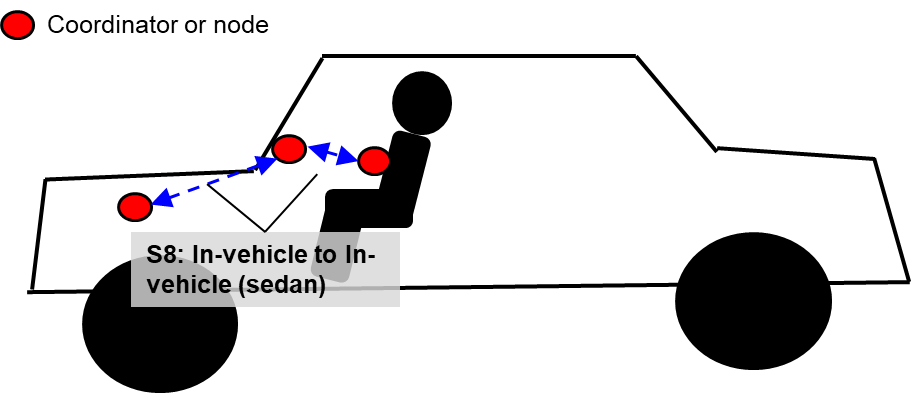
1. — 6.5.1.1 Engine compartment to engine compartment (Scenario 8.X, CM X)

The model was defined as UWB channel model for industrial environments in [22] which was extracted based on measurements that cover a range from 2 to 8 m, though the path gain also relies on values from the literature, 3-8m. The measurements are described in [23] .

1. —Parameters for Scenario 8 (CM8 and CMx) 3.1 - 10.6GHz

|  |  |  |  |
| --- | --- | --- | --- |
| Industrial | LOS | NLOS |  |
| valid range of d | 2 - 8 m | 2 - 8 m | comments |
| **Pathloss** |  |  | valid up to 10 m distance |
| *n* | 1.2 | 2.15 | NLOS case taken from [24] |
| σs [dB] | 6 | 6 | extracted from measurements of[24] , [25] |
| PL0 [dB] | 56.7 | 56.7 |  |
| *A*ant | 3 dB | 3dB |  |
| *k* | -1.103 | -1.427 |  |
| **Power delay profile** |  |  |  |
|  | 4.75 | 1 | The NLOS case is described by a single PDP shape |
| Λ [1/ns] | 0.0709 | NA |  |
| λ [1/ns] | NA | NA |  |
| Γ | 13.47 | NA |  |
| *k*γ | 0.926 | NA |  |
| γ0 | 0.651 | NA |  |
| σcluster [dB] | 4.32 | NA |  |
| **Small-scale fading** |  |  |  |
| *m*0 | 0.36 dB | 0.30 dB |  |
| *km* | 0 | 0 |  |
|  | 1.13 | 1.15 |  |
|  | 0 | 0 |  |
| [dB] | 12.99 |  | only for first cluster; *all* later components have same *m* |
| χ | NA | 1 |  |
| γrise[ns] | NA | 17.35 |  |
| γ1 [ns] | NA | 85.36 |  |

* + - * 1. In-vehicle to In-vehicle (Scenario 8, CM 8) 3.1 - 10.6GHz



1. —In-vehicle to In-vehicle (Scenario 8.X, CM X)

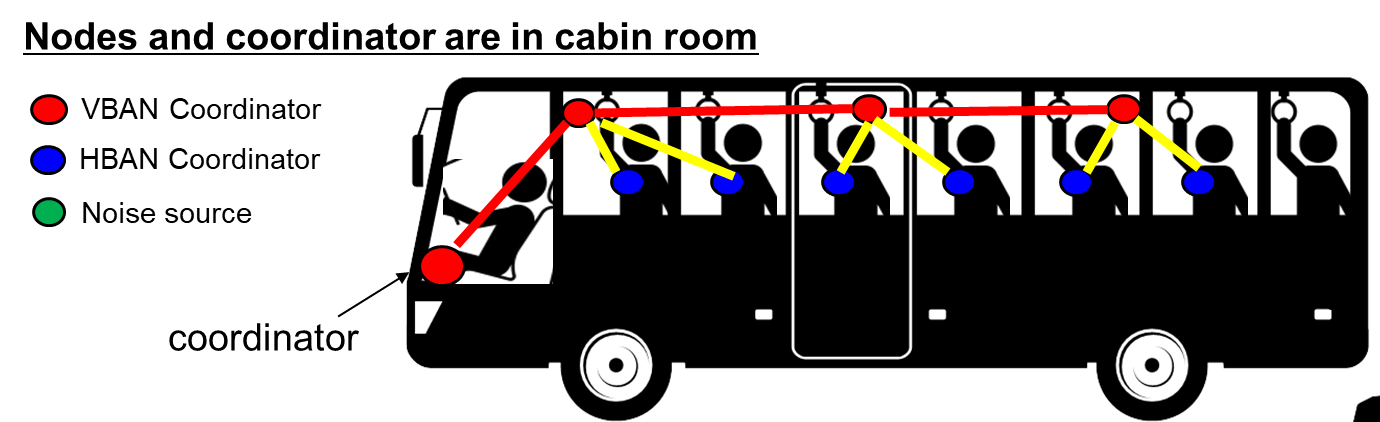
The model was defined as UWB channel model for residential environments in [22] which was extracted based on measurements that cover a range from 7-20m, up to 10 GHz. The derivation and justification of the parameters can be found in document [04-452], and all measurements are included in [04-290]

1. — Parameters for Scenario 8 (CM8 and CM8) 3.1 - 10.6GHz

|  |  |  |
| --- | --- | --- |
|  | LOS | NLOS |
| valid range of d | 7 - 20 m | 7 - 20 m |
| **Path gain** |  |  |
| *PL*0 [dB] | -43.9 | -48.7 |
| *n* | 1.79 | 4.58 |
| *S* [dB] | 2.22 | 3.51 |
| *κ* | 1.12 ± 0.12 | 1.53 ± 0.32 |
| **Power delay profile** |  |  |
|  | 3 | 3.5 |
| Λ [1/ns] | 0.047 | 0.12 |
| λ1, λ2 [1/ns], β | 1.54, 0.15, 0.095 | 1.77, 0.15, 0.045 |
| Γ [ns] | 22.61 | 26.27 |
| *k*γ | 0 | 0 |
| γ0 [ns] | 12.53 | 17.50 |
| σcluster [dB] | 2.75 | 2.93 |
| **Small-scale fading** |  |  |
| *m*0 [dB] | 0.67 | 0.69 |
| *km* | 0 | 0 |
| [dB] | 0.28 | 0.32 |
|  | 0 | 0 |
| [dB] | NA : all paths have | same m-factor distribution |

* + - 1. Cabin room to cabin room in omnibus (Scenario 8.1) 3.1 - 10.6GHz

In large vehicle like omnibus type of vehicle, multiple HBAN is in the same cabin room. In such situation, channel model CM8.1 can be applied to analyze communication between VBAN and multiple HBANs.

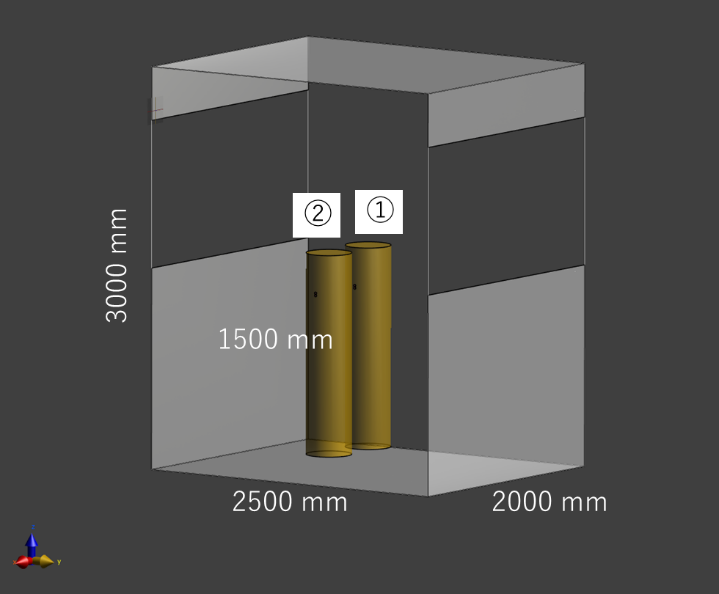


1. —Scenario8.1 for Omnibus HBANs to VBAN connection

In multiple passengers on a vehicle such as omnibus, VBAN coordinator is connected with multiple VBAN nodes and also connected with HBAN coordinator as well as HBAN nodes that is used passengers personally. In this situation channel models are defined as three ways bellow.

OPTION 1

Option 1 is based on a FDTD method simulation with simplified bus and human body tissue models[13] . . This model provides simulated path-loss in omnibus emvironment.



1. —simplified omnibus 3D models for FDTD simulation
2. On-vehicle to on-vehicle pathloss model parameters in S8.1

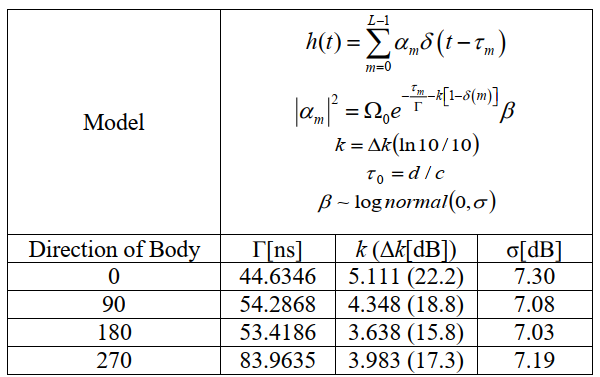
|  |  |  |  |
| --- | --- | --- | --- |
|  | *PL(d0) (dB)* | *n* | *σ2 (dB)* |
| LOS | xxx | Xxx | xxx |
|  |  |  |  |

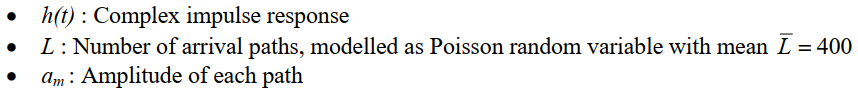
OPTION 2

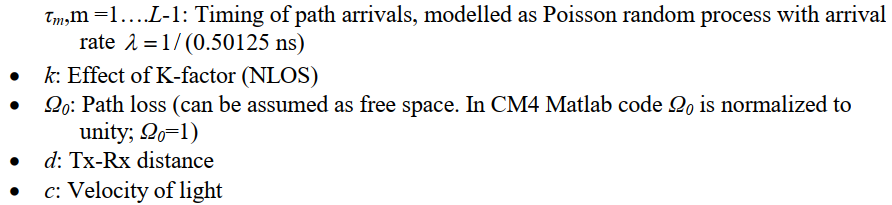
Option 1 is based on a channel model on IEEE802.15.6-2012 channel models document[1] . This is suitable to use for more focusing on HBAN centric analysis.

Measurement for the UWB frequency band of 3.1-10.6 GHz has been performed in [1] . On body antenna characteristics were measured in anechoic chamber, while channel measurements were done in office environment. For this measurement, the Tx antenna is fixed near to wall, while the Rx antenna (placed on body) positions were changed in office area. The effect of ground is considered in measurements. All data were averaged for statically analysis; therefore, the detail data of each measurement is not provided. The Further detail on set-up, derivation and data analysis can be found in [20] . The following figures summarize the delay profile of front, side, and backside of body while the Tx antenna is in the front of body.

1. Parameters of the path loss model for CM8.1 (Scenario S8.1) for 3.1-10.6 GHz







This model is commonly used for CM4 for HBAN.

OPTION 3

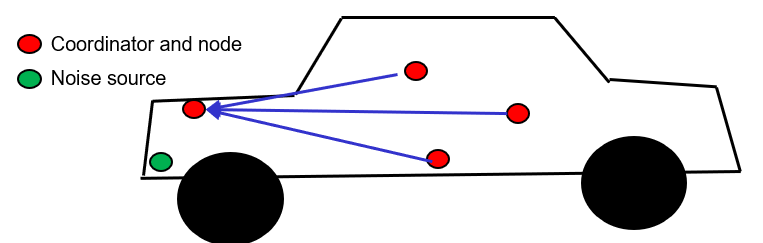
Option 2 is based on a channel model on IEEE802.15.4a channel model final report[22] . This is suitable to use for more focusing on VBAN centric analysis.

The model was defined as UWB channel model for residential environments in[22] which was extracted based on measurements that cover a range from 7-20m, up to 10 GHz. The derivation and justification of the parameters can be found in document [04-452], and all measurements are included in [04-290]

1. — Parameters for Scenario 8.X (CM8.X and CM8.x) 3.1 - 10.6GHz

|  |  |  |
| --- | --- | --- |
|  | LOS | NLOS |
| valid range of d | 7 - 20 m | 7 - 20 m |
| **Path gain** |  |  |
| *PL*0 [dB] | -43.9 | -48.7 |
| *n* | 1.79 | 4.58 |
| *S* [dB] | 2.22 | 3.51 |
| *κ* | 1.12 ± 0.12 | 1.53 ± 0.32 |
| **Power delay profile** |  |  |
|  | 3 | 3.5 |
| Λ [1/ns] | 0.047 | 0.12 |
| λ1, λ2 [1/ns], β | 1.54, 0.15, 0.095 | 1.77, 0.15, 0.045 |
| Γ [ns] | 22.61 | 26.27 |
| *k*γ | 0 | 0 |
| γ0 [ns] | 12.53 | 17.50 |
| σcluster [dB] | 2.75 | 2.93 |
| **Small-scale fading** |  |  |
| *m*0 [dB] | 0.67 | 0.69 |
| *km* | 0 | 0 |
| [dB] | 0.28 | 0.32 |
|  | 0 | 0 |
| [dB] | NA : all paths have | same m-factor distribution |

* + - * 1. Cabin room to engine compartment [asymmetric] (Scenario 8.X, CM X) 3.1 – 10.6GHz



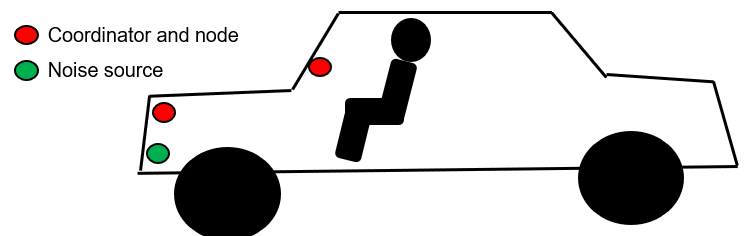
1. —Cabin room to engine compartment (Scenario 8.X, CM X)

TBD

1. Cabin room to engine compartment parameters [TBD]

|  |  |  |  |
| --- | --- | --- | --- |
| Direction | *PL(d0) (dB)* | *n* | *σ2 (dB)* |
| Cabin room to engine compartment | [TBD] | xxx | Xxx |
| Engine compartment to cabin room | xxx | Xxx | xxx |

* + - * 1. Engine compartment to cabin room [symmetric] (Scenario 8.X CMx) 3.1 - 10.6GHz



1. —Engine compartment to cabin room (Scenario 8.X CMx)

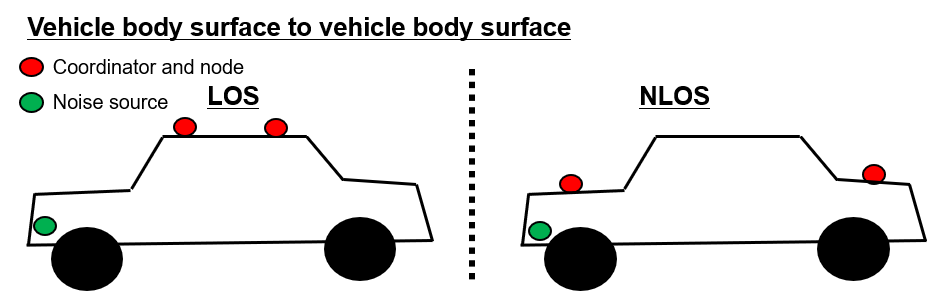
TBD

1. Cabin room to engine compartment pathloss model parameters [TBD]

|  |  |  |  |
| --- | --- | --- | --- |
| Direction | *PL(d0) (dB)* | *n* | *σ2 (dB)* |
| Cabin room to engine compartment | Xxx | xxx | Xxx |
| Engine compartment to cabin room | xxx | Xxx | xxx |

* 1. On vehicle

On-vehicle to on-vehicle (Scenario 11, 12, CM11, 12)



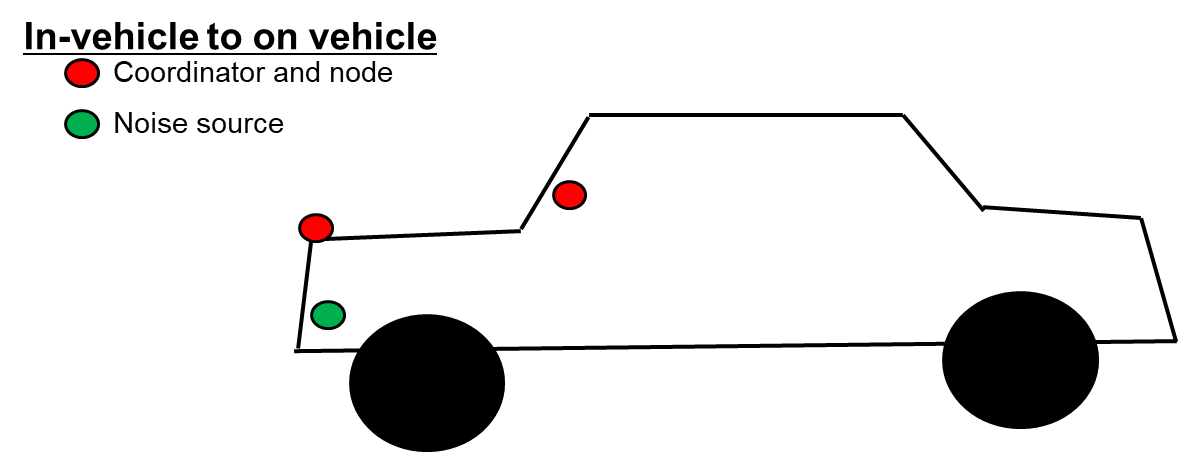
1. —On-vehicle to on-vehicle (Scenario 11, 12, CM 11, 12)

TBD

1. On-vehicle to on-vehicle pathloss model parameters [TBD]

|  |  |  |  |
| --- | --- | --- | --- |
|  | *PL(d0) (dB)* | *n* | *σ2 (dB)* |
| LOS (S11) | Xxx | xxx | Xxx |
| NLOS (S12) | xxx | Xxx | xxx |

In-vehicle to on vehicle (Scenario 9, CM9) 3.1 – 10.6 GHz



1. ―In-vehicle to on vehicle (Scenario 9, CM9) 3.1 – 10.6 GHz

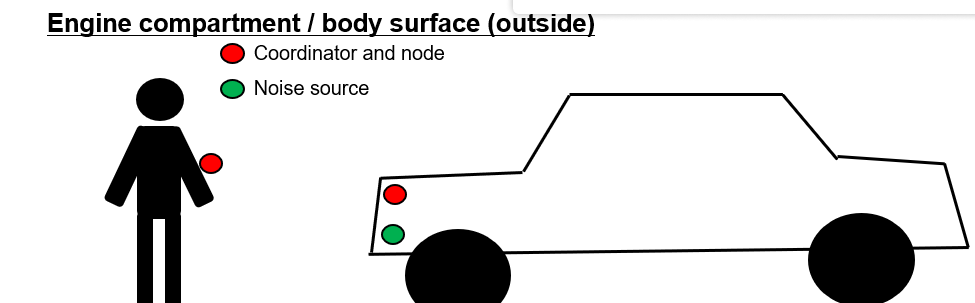
TBD

1. On-vehicle to on-vehicle pathloss model parameters [TBD]

|  |  |  |  |
| --- | --- | --- | --- |
|  | *PL(d0) (dB)* | *n* | *σ2 (dB)* |
| NLOS | xxx | Xxx | xxx |
|  |  |  |  |

* 1. External

In-vehicle to External (Scenario 10, CM 10) 3.1 – 10.6GHz



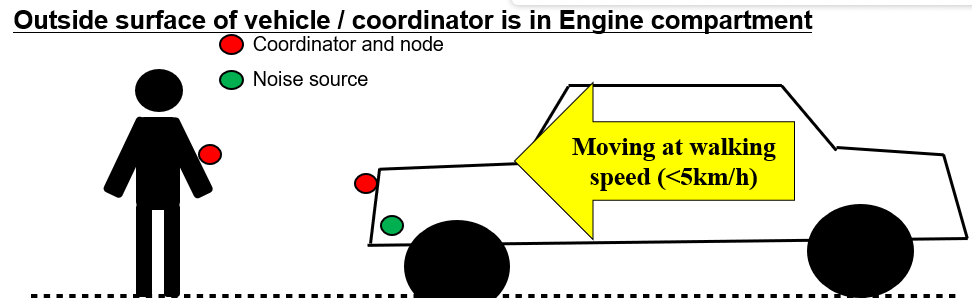
1. —In-vehicle to external (Scenario 10, CM10) 3.1 – 10.6 GHz

The model was extracted based on measurements that cover a range from 5-17m, 3-6 GHz. A description of the model derivation can be found in [04-383, 04-385, 04-439, 04-440]. The Farm area model was extracted based on measurements in a snow-covered open area, and simulations of a farm area. The derivation of the model and a description of the simulations (for the farm area) can be found in [04-475]

1. Parameters of the channel models for Scenario 10, CM 10

|  |  |  |  |
| --- | --- | --- | --- |
| **Outdoor** | **LOS** | **NLOS** | **Farm(LOS)** |
| valid range of d | 5 - 17 m | 5 - 17 m |  |
| **Pathloss** |  |  |  |
| *n* | 1.76 | 2.5 | 1.58 |
| *σS* | 0.83 | 2 | 3.96 |
| *PL*0 | 45.6 | 73.0 | 48.96 |
| *A*ant [dB] | 3 | 3 | 3 |
| *κ* | 0.12 | 0.13 | 0 |
| **Power delay profile** |  |  |  |
| L | 13.6 | 10.5 | 3.31 |
| Λ [1/ns] | 0.0048 | 0.0243 | 0.0305 |
| *λ*1 [1/ns] | 0.27 | 0.15 | 0.0225 |
| *λ*2 [1/ns] | 2.41 | 1.13 | 0 |
| *β* | 0.0078 | 0.062 | 0 |
| Γ [ns] | 31.7 | 104.7 | 56 |
| *k*γ | 0 | 0 | 0 |
| γ0 [ns] | 3.7 | 9.3 | 0.92 |
| σcluster [dB] | 3 |  |  |
| **Small-scale fading** |  |  |  |
| m0 | 0.77 dB | 0.56 dB | 4.1 dB |
| *km* | 0 | 0 | 0 |
|  | 0.78 | 0.25 | 2.5 dB |
|  | 0 | 0 | 0 |
|  | NA | NA | 0 |
| *χ* | NA | NA | NA |
| γrise | NA | NA | NA |
| γ1 | NA | NA | NA |

* + 1. On-vehicle to External with mobility consideration (Scenario 13 & 14 & 13)



1. —On-vehicle to External with mobility consideration (Scenario 13 & 14, CM 13)
2. — Parameters of the channel models for Scenarios 13 & 14 & X, CM X

|  |  |  |  |
| --- | --- | --- | --- |
| Outdoor | LOS | NLOS | Farm |
| valid range of d | 5 - 17 m | 5 - 17 m |  |
| Path gain |  |  |  |
| n | 1.76 | 2.5 | 1.58 |
| σS | 0.83 | 2 | 3.96 |
| G0 | -45.6 | -73.0 | -48.96 |
| κ | 0.12 | 0.13 | 0 |
| Power delay profile |  |  |  |
| L | 13.6 | 10.5 | 3.31 |
| Λ [1/ns] | 0.0048 | 0.0243 | 0.0305 |
| λ1 [1/ns] | 0.27 | 0.15 | 0.0225, 0, 0 |
| λ2 [1/ns] | 2.41 | 1.13 |  |
| β | 0.0078 | 0.062 |  |
| Γ [ns] | 31.7 | 104.7 | 56 |
| k γ | 0 | 0 | 0 |
| γ0 [ns] | 3.7 | 9.3 | 0.92 |
| σcluster [dB] | 3 |  |  |
| Small-scale fading |  |  |  |
| m0 | 0.77 dB | 0.56 dB | 4.1 dB |
| mb 0 | 0.78 | 0.25 | 2.5 dB |
| me 0 | NA | NA | 0 |

# Bibliography

1. Kamya Yekeh Yazdandoost, Kamran Sayrafian-Pour, “Channel Model for Body Area Network (BAN),” IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), IEEE P802.15-08-0780-12-0006, Nov., 2012.
2. W.-T. Chen; H.-R. Chuang, “Numerical computation of human interaction with arbitrarily oriented superquadric loop antennas in personal communications,” IEEE Trans. on Antenna and Propagation, vol.46, no. 6, pp. 821-828, June 1998.
3. Kamya Y. Yazdandoost and Ryuji Kohno, “The Effect of Human Body on UWB BAN Antennas,” IEEE802.15-07-0546-00-0ban.
4. C. H. Duney, H. Massoudi, and M. F. Iskander, “Radiofrequency radiation dosimetry handbook,” USAF School of Aerospace Medicine, October 1986.
5. C. Gabriel and S. Gabriel, “Compilation of the dielectric properties of body tissues at RF and microwave frequencies,” AL/OE-TR-1996-0037, June 1996, <http://www.brooks.af.mil/AFRL/HED/hedr/reports/dielectricReport/Report.html>.
6. Italian National Research Council, Institute for Applied Physics, “Dielectric properties of body tissues,” <http://niremf.ifac.cnr.it>
7. P. Gandhi, “.Biological effects and medical applications of electromagnetic energy,” Prentice Hall, Englewood Cliffs, N.J., 1990.
8. Marco Hernandez, Huan-Bang Li, Igor Dotlić, Ryu Miura, “Channel Models for TG8,” IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), IEEE P802. 15-12-0459-07-0008, Sept., 2012
9. 3GPP TS 36.104, Evolved Universal Terrestrial Radio Access; Base Station radio transmission and reception
10. E. Reusens, W. Joseph, G. Vermeeren, and L. Martens, „On-body measurements and characterization of wireless communication channel fro arm and torso of human,“ International Workshop on Wearable and Implantabel Body Sensor Networks, BSN07, Achen, March 2007, pp. 26-28.
11. A. Fort, J. Ryckaert, C. Desset, P. De Doncker, P. Wambacq, and L. Van Biesen, “ Ultrawideband channel model for communication around the human body, ” IEEE Journal on Selected Areas in Communications, vol. 24, pp.927-933, April 2006.
12. Kamran Sayrafian, doc.# P.802.15-22-0401-00-6a, 2022.
13. Daisuke Anzai, “Propagation characteristics of UWB communication applications including medical implants, BCI and passengers bus,” doc.# P.802. 15-22-0469-00-006a, 2022
14. D. Anzai, I. Balasingham, G. Fischer, J. Wang, "Reliable and High-Speed Implant Ultra-Wideband Communications with Transmit-Receive Diversity," EAI/Springer Innovations in Communication and Computing, pp. 27-32, March 2020.
15. Y. Shimizu, D. Anzai, R. C-Santiago, P. A. Floor, I. Balasingham, and J. Wang, "Performance evaluation of an ultra-wideband transmit diversity in a living animal experiment" IEEE Trans. Microw. Theory Tech., vol. 65, no. 7, pp. 2596-2606, July 2017.
16. D. Anzai, K. Katsu, R. Chavez-Santiago, Q. Wang, D. Plettemeier, J. Wang, and I. Balasingham, "Experimental evaluation of implant UWB-IR transmission with living animal for body area networks," IEEE Trans. Microw. Theory Tech., vol. 62, no. 1, pp. 183-192, Jan. 2014.
17. J. Shi, D. Anzai, and J. Wang, "Channel modeling and performance analysis of diversity reception for implant UWB wireless link," IEICE Trans. Commun., no. E95-B, vol. 10, pp. 3197-3205, Oct. 2012.
18. Takahiro Aoyagi, Jun-ichi Takada, Kenichi Takizawa, Norihiko Katayama, Takehiko Kobayashi, Kamya Yekeh Yazdandoost, Huan-bang Li and Ryuji Kohno, “Channel model for wearable and implantable WBANs,” IEEE 802.15-08-0416-04-0006, November 2008.
19. Guido Dolmans and Andrew Fort, “Channel models WBAN-Holst centre/IMEC-NL,” IEEE 802.15-08-0418-01-0006, July 2008.
20. Hirokazu Sawada, Takahiro Aoyagi, Jun-ichi Takada, Kamya Yekeh Yazdandoost, Ryuji Kohno, “Channel model between body surface and wireless access point for UWB band,” IEEE 802.15-08-0576-00-0006, August 2008.
21. Minseok Kim, Jun-ichi Takada, Bin Zhen, Lawrence Materum, Tomoshige Kan, Yuuki Terao, yohei Konishi, Kenji Nakai, Takahiro Aoyagi, Ryuji Kohno, “Statistical property of dynamic BAN channel gain at 4.5 GHz,” IEEE 802-.15-08-0489-02-0006, June 2010.
22. Andreas F. Molisch, Kannan Balakrishnan, Dajana Cassioli, Chia-Chin Chong, Shahriar Emami, Andrew Fort,Johan Karedal, Juergen Kunisch, Hans Schantz, Ulrich Schuster, Kai Siwiak, “IEEE 802.15.4a channel model - final report,”
23. J. Karedal, S. Wyne, P. Almers, F. Tufvesson, and A. F. Molisch, “Statistical analysis of the uwb channel in an industrial environment,” in Proc. VTC fall 2004, 2004.
24. T. S. Rappaport 1989.
25. W. Pietsch 1994.

# (informative) Matlab code for IEEE802.15.4a UWB channel model

% modified S-V channel model evaluation

%%Written by Sun Xu, Kim Chee Wee, B. Kannan & Francois Chin on 22/02/2005

clear;

no\_output\_files = 1; % non-zero: avoids writing output files of continuous-time responses

num\_channels = 100; % number of channel impulse responses to generate

randn(’state’,12); % initialize state of function for repeatability

rand(’state’,12); % initialize state of function for repeatability

cm\_num = 6; % channel model number from 1 to 8

% get channel model params based on this channel model number

[Lam,Lmean,lambda\_mode,lambda\_1,lambda\_2,beta,Gam,gamma\_0,Kgamma, ...

sigma\_cluster,nlos,gamma\_rise,gamma\_1,chi,m0,Km,sigma\_m0,sigma\_Km, ...

sfading\_mode,m0\_sp,std\_shdw,kappa,fc,fs] = uwb\_sv\_params\_15\_4a( cm\_num );

fprintf(1,[’Model Parameters\n’ ...

’ Lam = %.4f, Lmean = %.4f, lambda\_mode(FLAG) = %d\n’ ...

’ lambda\_1 = %.4f, lambda\_2 = %.4f, beta = %.4f\n’ ...

’ Gam = %.4f, gamma0 = %.4f, Kgamma = %.4f, sigma\_cluster = %.4f\n’ ...

’ nlos(FLAG) = %d, gamma\_rise = %.4f, gamma\_1 = %.4f, chi = %.4f\n’ ...

’ m0 = %.4f, Km = %.4f, sigma\_m0 = %.4f, sigma\_Km = %.4f\n’ ...

’ sfading\_mode(FLAG) = %d, m0\_sp = %.4f, std\_shdw = %.4f\n’, ...

’ kappa = %.4f, fc = %.4fGHz, fs = %.4fGHz\n’], ...

Lam,Lmean,lambda\_mode,lambda\_1,lambda\_2,beta,Gam,gamma\_0,Kgamma, ...

sigma\_cluster,nlos,gamma\_rise,gamma\_1,chi,m0,Km,sigma\_m0,sigma\_Km,...

sfading\_mode,m0\_sp,std\_shdw,kappa,fc,fs);

ts = 1/fs; % sampling frequency

% get a bunch of realizations (impulse responses)

[h\_ct,t\_ct,t0,np] = uwb\_sv\_model\_ct\_15\_4a(Lam,Lmean,lambda\_mode,lambda\_1, ...

lambda\_2,beta,Gam,gamma\_0,Kgamma,sigma\_cluster,nlos,gamma\_rise,gamma\_1, ...

chi,m0,Km,sigma\_m0,sigma\_Km,sfading\_mode,m0\_sp,std\_shdw,num\_channels,ts);

% change to complex baseband channel

h\_ct\_len = size(h\_ct, 1);

phi = zeros(h\_ct\_len, 1);

for k = 1:num\_channels

phi = rand(h\_ct\_len, 1).\*(2\*pi);

h\_ct(:,k) = h\_ct(:,k) .\* exp(phi .\* i);

end

% now reduce continuous-time result to a discrete-time result

[hN,N] = uwb\_sv\_cnvrt\_ct\_15\_4a( h\_ct, t\_ct, np, num\_channels, ts );

if N > 1,

h = resample(hN, 1, N); % decimate the columns of hN by factor N

else

h = hN;

end

% add the frequency dependency

[h]= uwb\_sv\_freq\_depend\_ct\_15\_4a(h,fc,fs,num\_channels,kappa);

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

% Testing and ploting

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

% channel energy

channel\_energy = sum(abs(h).^2);

h\_len = length(h(:,1));

t = [0:(h\_len-1)] \* ts; % for use in computing excess & RMS delays

excess\_delay = zeros(1,num\_channels);

RMS\_delay = zeros(1,num\_channels);

num\_sig\_paths = zeros(1,num\_channels);

num\_sig\_e\_paths = zeros(1,num\_channels);

for k=1:num\_channels

% determine excess delay and RMS delay

sq\_h = abs(h(:,k)).^2 / channel\_energy(k);

t\_norm = t - t0(k); % remove the randomized arrival time of first cluster

excess\_delay(k) = t\_norm \* sq\_h;

RMS\_delay(k) = sqrt( ((t\_norm-excess\_delay(k)).^2) \* sq\_h );

% determine number of significant paths (paths within 10 dB from peak)

threshold\_dB = -10; % dB

temp\_h = abs(h(:,k));

temp\_thresh = 10^(threshold\_dB/20) \* max(temp\_h);

num\_sig\_paths(k) = sum(temp\_h > temp\_thresh);

% determine number of sig. paths (captures x % of energy in channel)

x = 0.85;

temp\_sort = sort(temp\_h.^2); % sorted in ascending order of energy

cum\_energy = cumsum(temp\_sort(end:-1:1)); % cumulative energy

index\_e = min(find(cum\_energy >= x \* cum\_energy(end)));

num\_sig\_e\_paths(k) = index\_e;

end

energy\_mean = mean(10\*log10(channel\_energy));

energy\_stddev = std(10\*log10(channel\_energy));

mean\_excess\_delay = mean(excess\_delay);

mean\_RMS\_delay = mean(RMS\_delay);

mean\_sig\_paths = mean(num\_sig\_paths);

mean\_sig\_e\_paths = mean(num\_sig\_e\_paths);

fprintf(1,’Model Characteristics\n’);

fprintf(1,’ Mean delays: excess (tau\_m) = %.1f ns, RMS (tau\_rms) = %1.f\n’, ...

mean\_excess\_delay, mean\_RMS\_delay);

fprintf(1,’ # paths: NP\_10dB = %.1f, NP\_85%% = %.1f\n’, ...

mean\_sig\_paths, mean\_sig\_e\_paths);

fprintf(1,’ Channel energy: mean = %.1f dB, std deviation = %.1f dB\n’, ...

energy\_mean, energy\_stddev);

figure(1); clf; plot(t, abs(h)); grid on

title(’Impulse response realizations’)

xlabel(’Time (nS)’)

figure(2); clf; plot([1:num\_channels], excess\_delay, ’b-’, ...

[1 num\_channels], mean\_excess\_delay\*[1 1], ’r–’ );

grid on

title(’Excess delay (nS)’)

xlabel(’Channel number’)

figure(3); clf; plot([1:num\_channels], RMS\_delay, ’b-’, ...

[1 num\_channels], mean\_RMS\_delay\*[1 1], ’r–’ );

grid on

title(’RMS delay (nS)’)

xlabel(’Channel number’)

figure(4); clf; plot([1:num\_channels], num\_sig\_paths, ’b-’, ...

[1 num\_channels], mean\_sig\_paths\*[1 1], ’r–’);

grid on

title(’Number of significant paths within 10 dB of peak’)

xlabel(’Channel number’)

figure(5); clf; plot([1:num\_channels], num\_sig\_e\_paths, ’b-’, ...

[1 num\_channels], mean\_sig\_e\_paths\*[1 1], ’r–’);

grid on

title(’Number of significant paths capturing > 85% energy’)

xlabel(’Channel number’)

temp\_average\_power = sum((abs(h))’.\*(abs(h))’, 1)/num\_channels;

temp\_average\_power = temp\_average\_power/max(temp\_average\_power);

average\_decay\_profile\_dB = 10\*log10(temp\_average\_power);

threshold\_dB = -40;

above\_threshold = find(average\_decay\_profile\_dB > threshold\_dB);

ave\_t = t(above\_threshold);

apdf\_dB = average\_decay\_profile\_dB(above\_threshold);

figure(6); clf; plot(ave\_t, apdf\_dB); grid on

title(’Average Power Decay Profile’)

xlabel(’Delay (nsec)’)

ylabel(’Average power (dB)’)

if no\_output\_files,

return

end

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

%Savinge the data

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

%%% save continuous-time (time,value) pairs to files

save\_fn = sprintf(’cm%d\_imr’, cm\_num);

% A complete self-contained file for Matlab users

save([save\_fn ’.mat’], ’t’, ’h’,’t\_ct’, ’h\_ct’, ’t0’, ’np’, ’num\_channels’, ’cm\_num’);

% Three comma-delimited text files for non-Matlab users:

% File #1: cmX\_imr\_np.csv lists the number of paths in each realization

dlmwrite([save\_fn ’\_np.csv’], np, ’,’); % number of paths

% File #2: cmX\_imr\_ct.csv can open with Excel

% n’th pair of columns contains the (time,value) pairs for the n’th realization

% save continous time data

th\_ct = zeros(size(t\_ct,1),3\*size(t\_ct,2));

th\_ct(:,1:3:end) = t\_ct; % time

th\_ct(:,2:3:end) = abs(h\_ct); % magnitude

th\_ct(:,3:3:end) = angle(h\_ct); % phase (radians)

fid = fopen([save\_fn ’\_ct.csv’], ’w’);

if fid < 0,

error(’unable to write .csv file for impulse response, file may be open in another application’);

end

for k = 1:size(th\_ct,1)

fprintf(fid,’%.4f,%.6f,’, th\_ct(k,1:end-2));

fprintf(fid,’%.4f,%.6f\r\n’, th\_ct(k,end-1:end)); % \r\n for Windoze end-of-line

end

fclose(fid);

% File #3: cmX\_imr\_dt.csv can open with Excel

% discrete channel impulse response magnitude and phase pair realization.

% the first column is time. phase is in radians

% save discrete time data

th = zeros(size(h,1),2\*size(h,2)+1);

th(:,1) = t’; % the first column is time scale

th(:,2:2:end) = abs(h); % even columns are magnitude

th(:,3:2:end) = angle(h); % odd columns are phase

fid = fopen([save\_fn ’\_dt.csv’], ’w’);

if fid < 0,

error(’unable to write .csv file for impulse response, file may be open in another application’);

end

for k = 1:size(th,1)

fprintf(fid,’%.4f,%.6f,’, th(k,1:end-2));

fprintf(fid,’%.4f,%.6f\r\n’, th(k,end-1:end)); % \r\n for Windoze end-of-line

end

fclose(fid);

return; % end of program

function [Lam,Lmean,lambda\_mode,lambda\_1,lambda\_2,beta,Gam,gamma\_0,Kgamma, ...

sigma\_cluster,nlos,gamma\_rise,gamma\_1,chi,m0,Km,sigma\_m0,sigma\_Km, ...

sfading\_mode,m0\_sp,std\_shdw,kappa,fc,fs] = uwb\_sv\_params\_15\_4a( cm\_num )

% Written by Sun Xu, Kim Chee Wee, B. Kannan & Francois Chin on 22/02/2004

% Return modified S-V model parameters for standard UWB channel models

%————————————————————————–

% Lam Cluster arrival rate (clusters per nsec)

% Lmean Mean number of Clusters

% lambda\_mode Flag for Mixture of poission processes for ray arrival times

% 1 -> Mixture of poission processes for the ray arrival times

% 2 -> tapped delay line model

% lambda\_1 Ray arrival rate for Mixture of poisson processes (rays per nsec)

% lambda\_2 Ray arrival rate for Mixture of poisson processes (rays per nsec)

% beta Mixture probability

%————————————————————————–

% Gam Cluster decay factor (time constant, nsec)

% gamma0 Ray decay factor (time constant, nsec)

% Kgamma Time dependence of ray decay factor

% sigma\_cluster Standard deviation of normally distributed variable for cluster energy

% nlos Flag for non line of sight channel

% 0 -> LOS

% 1 -> NLOS with first arrival path starting at t ~= 0

% 2 -> NLOS with first arrival path starting at t = 0 and diffused first cluster

% gamma\_rise Ray decay factor of diffused first cluster (time constant, nsec)

% gamma\_1 Ray decay factor of diffused first cluster (time constant, nsec)

% chi Diffuse weight of diffused first cluster

%————————————————————————–

% m0 Mean of log-normal distributed nakagami-m factor

% Km Time dependence of m0

% sigma\_m0 Standard deviation of log-normal distributed nakagami-m factor

% sigma\_Km Time dependence of sigma\_m0

% sfading\_mode Flag for small-scale fading

% 0 -> All paths have same m-factor distribution

% 1 -> LOS first path has a deterministic large m-factor

% 2 -> LOS first path of each cluster has a deterministic

% large m-factor

% m0\_sp Deterministic large m-factor

%————————————————————————–

% std\_shdw Standard deviation of log-normal shadowing of entire impulse response

%————————————————————————–

% kappa Frequency dependency of the channel

%————————————————————————–

% fc Center Frequency

% fs Frequency Range

%%

modified by I2R

if cm\_num == 1, % Residential LOS

% MPC arrival

Lam = 0.047; Lmean = 3;

lambda\_mode = 1;

lambda\_1 = 1.54; lambda\_2 = 0.15; beta = 0.095;

%MPC decay

Gam = 22.61; gamma\_0 = 12.53; Kgamma = 0; sigma\_cluster = 2.75;

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.67; Km = 0; sigma\_m0 = 0.28; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN;

% Large-scale Fading – Shadowing

std\_shdw = 2.22;

% Frequency Dependence

kappa = 1.12;

fc = 6; % GHz

fs = 8; % 2 - 10 GHz

elseif cm\_num == 2, % Residential NLOS

% MPC arrival

Lam = 0.12; Lmean = 3.5;

lambda\_mode = 1;

lambda\_1 = 1.77; lambda\_2 = 0.15; beta = 0.045;

%MPC decay

Gam = 26.27; gamma\_0 = 17.5; Kgamma = 0; sigma\_cluster = 2.93;

nlos = 1;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.69; Km = 0; sigma\_m0 = 0.32; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN;

% Large-scale Fading – Shadowing

std\_shdw = 3.51;

% Frequency Dependence

kappa = 1.53;

fc = 6; % GHz

fs = 8; % 2 - 10 GHz

elseif cm\_num == 3, % Office LOS

% MPC arrival

Lam = 0.016; Lmean = 5.4;

lambda\_mode = 1;

lambda\_1 = 0.19; lambda\_2 = 2.97; beta = 0.0184;

%MPC decay

Gam = 14.6; gamma\_0 = 6.4; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.42; Km = 0; sigma\_m0 = 0.31; sigma\_Km = 0;

sfading\_mode = 2; m0\_sp = 3; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 0; %1.9;

% Frequency Dependence

kappa = 0.03;

fc = 6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 4, % Office NLOS

% MPC arrival

Lam = 0.19; Lmean = 3.1;

lambda\_mode = 1;

lambda\_1 = 0.11; lambda\_2 = 2.09; beta = 0.0096;

%MPC decay

Gam = 19.8; gamma\_0 = 11.2; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 2;

gamma\_rise = 15.21; gamma\_1 = 11.84; chi = 0.78;

% Small-scale Fading

m0 = 0.5; Km = 0; sigma\_m0 = 0.25; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 3.9;

% Frequency Dependence

kappa =0.71;

fc = 6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 5, % Outdoor LOS

% MPC arrival

Lam = 0.0448; Lmean = 13.6;

lambda\_mode = 1;

lambda\_1 = 0.13; lambda\_2 = 2.41; beta = 0.0078;

%MPC decay

Gam = 31.7; gamma\_0 = 3.7; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.77; Km = 0; sigma\_m0 = 0.78; sigma\_Km = 0;

sfading\_mode = 2; m0\_sp = 3; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 0.83;

% Frequency Dependence

kappa = 0.12;

fc = 6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 6, % Outdoor NLOS

% MPC arrival

Lam = 0.0243; Lmean = 10.5;

lambda\_mode = 1;

lambda\_1 = 0.15; lambda\_2 = 1.13; beta = 0.062;

%MPC decay

Gam = 104.7; gamma\_0 = 9.3; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 1;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.56; Km = 0; sigma\_m0 = 0.25; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 2; % assumption

% Frequency Dependence

kappa = 0.13;

fc =6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 7, % Industrial LOS

% MPC arrival

Lam = 0.0709; Lmean = 4.75;

lambda\_mode = 2;

lambda\_1 = 1; lambda\_2 = 1; beta = 1; % dummy in this scenario

%MPC decay

Gam = 13.47; gamma\_0 = 0.615; Kgamma = 0.926; sigma\_cluster = 4.32;

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.36; Km = 0; sigma\_m0 = 1.13; sigma\_Km = 0;

sfading\_mode = 1; m0\_sp = 12.99;

% Large-scale Fading – Shadowing

std\_shdw = 6;

% Frequency Dependence

kappa = -1.103;

fc = 6; % GHz

fs = 8; % 2 - 8 GHz

elseif cm\_num == 8, % Industrial NLOS

% MPC arrival

Lam = 0.089; Lmean = 1;

lambda\_mode = 2;

lambda\_1 = 1; lambda\_2 = 1; beta = 1; % dummy in this scenario

%MPC decay

Gam = 5.83; gamma\_0 = 0.3; Kgamma = 0.44; sigma\_cluster = 2.88;

nlos = 2;

gamma\_rise = 47.23; gamma\_1 = 84.15; chi = 0.99;

% Small-scale Fading

m0 = 0.3; Km = 0; sigma\_m0 = 1.15; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % m0\_sp is assumption

% Large-scale Fading – Shadowing

std\_shdw = 6;

% Frequency Dependence

kappa = -1.427;

fc = 6; % GHz

fs = 8; % 2 - 8 GHz

elseif cm\_num == 9, % Open Outdoor Environment NLOS (Fram, Snow-Covered Open Area)

% MPC arrival

Lam = 0.0305; Lmean = 3.31;

lambda\_mode = 1;

lambda\_1 = 0.0225; lambda\_2 = 1; beta = 1;

%MPC decay

Gam = 56; gamma\_0 = 0.92; Kgamma = 0; sigma\_cluster = 3; % sigma\_cluster is assumption

nlos = 1;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN;

% Small-scale Fading

m0 = 4.1; Km = 0; sigma\_m0 = 2.5; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % m0\_sp is assumption

% Large-scale Fading – Shadowing

std\_shdw = 3.96;

% Frequency Dependence

kappa = -1; % Kappa is assumption

fc = 6; % GHz

fs = 8; % 2 - 8 GHz

else

error(’cm\_num is wrong!!’)

end

return

function [h]= uwb\_sv\_freq\_depend\_ct\_15\_4a(h,fc,fs,num\_channels,kappa)

% This function is used to include the frequency dependency

f0 = 5; % GHz

h\_len = length(h(:,1));

f = [fc-fs/2 : fs/h\_len/2 : fc+fs/2]./f0;

f = f.^(-2\*(kappa));

f = [f(h\_len : 2\*h\_len), f(1 : h\_len-1)]’;

i = (-1)^(1/2); % complex i

for c = 1:num\_channels

% add the frequency dependency

h2 = zeros(2\*h\_len, 1);

h2(1 : h\_len) = h(:,c); % zero padding

fh2 = fft(h2);

fh2 = fh2 .\* f;

h2 = ifft(fh2);

h(:,c) = h2(1:h\_len);

% Normalize the channel energy to 1

h(:,c) = h(:,c)/sqrt(h(:,c)’ \* h(:,c) );

end

return

function [h,t,t0,np] = uwb\_sv\_model\_ct\_15\_4a(Lam,Lmean,lambda\_mode,lambda\_1, ...

lambda\_2,beta,Gam,gamma\_0,Kgamma,sigma\_cluster,nlos,gamma\_rise,gamma\_1, ...

chi,m0,Km,sigma\_m0,sigma\_Km,sfading\_mode,m0\_sp,std\_shdw,num\_channels,ts)

% Written by Sun Xu, Kim Chee Wee, B. Kannan & Francois Chin on 22/02/2005

% IEEE 802.15.4a UWB channel model for PHY proposal evaluation

% continuous-time realization of modified S-V channel model

% Input parameters:

% detailed introduction of input parameters is at uwb\_sv\_params.m

% num\_channels number of random realizations to generate

% Outputs

% h is returned as a matrix with num\_channels columns, each column

% holding a random realization of the channel model (an impulse response)

% t is organized as h, but holds the time instances (in nsec) of the paths whose

% signed amplitudes are stored in h

% t0 is the arrival time of the first cluster for each realization

% np is the number of paths for each realization.

% Thus, the k’th realization of the channel impulse response is the sequence

% of (time,value) pairs given by (t(1:np(k),k), h(1:np(k),k))

%%

modified by I2R

% initialize and precompute some things

std\_L = 1/sqrt(2\*Lam); % std dev (nsec) of cluster arrival spacing

std\_lam\_1 = 1/sqrt(2\*lambda\_1);

std\_lam\_2 = 1/sqrt(2\*lambda\_2);

% std\_lam = 1/sqrt(2\*lambda); % std dev (nsec) of ray arrival spacing

h\_len = 1000; % there must be a better estimate of # of paths than this

ngrow = 1000; % amount to grow data structure if more paths are needed

h = zeros(h\_len,num\_channels);

t = zeros(h\_len,num\_channels);

t0 = zeros(1,num\_channels);

np = zeros(1,num\_channels);

for k = 1:num\_channels % loop over number of channels

tmp\_h = zeros(size(h,1),1);

tmp\_t = zeros(size(h,1),1);

if nlos == 1,

Tc = (std\_L\*randn)^2 + (std\_L\*randn)^2; % First cluster random arrival

else

Tc = 0; % First cluster arrival occurs at time 0

end

t0(k) = Tc;

if nlos == 2 & lambda\_mode == 2

L = 1; % for industrial NLOS environment

else

L = max(1, poissrnd(Lmean)); % number of clusters

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if Kgamma ~= 0 & nlos == 0

Tcval = []; Tc\_cluster= [];

Tc\_cluster(1,1)=Tc;

for i\_Tc=2:L+1

Tc\_cluster(1,i\_Tc)= Tc\_cluster(1,i\_Tc-1)+(std\_L\*randn)^2 + (std\_L\*randn)^2;

end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

cluster\_index = zeros(1,L);

path\_ix = 0;

nak\_m = [];

for ncluster = 1:L

% Determine Ray arrivals for each cluster

Tr = 0; % first ray arrival defined to be time 0 relative to cluster

cluster\_index(ncluster) = path\_ix+1; % remember the cluster location

gamma = Kgamma\*Tc + gamma\_0; % delay dependent cluster decay time

if nlos == 2 & ncluster == 1

gamma = gamma\_1;

end

Mcluster = sigma\_cluster\*randn;

Pcluster = 10\*log10(exp(-1\*Tc/Gam))+Mcluster; % total cluster power

Pcluster = 10^(Pcluster\*0.1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if Kgamma ~= 0 & nlos == 0

Tr\_len=Tc\_cluster(1,ncluster+1)-Tc\_cluster(1,ncluster);

else

Tr\_len = 10\*gamma;

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

while (Tr < Tr\_len),

t\_val = (Tc+Tr); % time of arrival of this ray

if nlos == 2 & ncluster == 1

% equation (22)

h\_val = Pcluster\*(1-chi\*exp(-Tr/gamma\_rise))\*exp(-Tr/gamma\_1) ...

\*(gamma+gamma\_rise)/gamma/(gamma+gamma\_rise\*(1-chi));

else

% equation (19)

h\_val = Pcluster/gamma\*exp(-Tr/gamma)/(beta\*lambda\_1+(1-beta)\*lambda\_2+1);

end

path\_ix = path\_ix + 1; % row index of this ray

if path\_ix > h\_len,

% grow the output structures to handle more paths as needed

tmp\_h = [tmp\_h; zeros(ngrow,1)];

tmp\_t = [tmp\_t; zeros(ngrow,1)];

h = [h; zeros(ngrow,num\_channels)];

t = [t; zeros(ngrow,num\_channels)];

h\_len = h\_len + ngrow;

end

tmp\_h(path\_ix) = h\_val;

tmp\_t(path\_ix) = t\_val;

% if lambda\_mode == 0

% Tr = Tr + (std\_lam\*randn)^2 + (std\_lam\*randn)^2;

if lambda\_mode == 1

if rand < beta

Tr = Tr + (std\_lam\_1\*randn)^2 + (std\_lam\_1\*randn)^2;

else

Tr = Tr + (std\_lam\_2\*randn)^2 + (std\_lam\_2\*randn)^2;

end

elseif lambda\_mode == 2

Tr = Tr + ts;

else

error(’lambda mode is wrong!’)

end

% generate log-normal distributed nakagami m-factor

m\_mu = m0 - Km\*t\_val;

m\_std = sigma\_m0 - sigma\_Km\*t\_val;

nak\_m = [nak\_m, lognrnd(m\_mu, m\_std)];

end

Tc = Tc + (std\_L\*randn)^2 + (std\_L\*randn)^2;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if Kgamma ~= 0 & nlos == 0

Tc = Tc\_cluster(1,ncluster+1);

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

end

% change m value of the first multipath to be the deterministic value

if sfading\_mode == 1

nak\_ms(cluster\_index(1)) = m0\_sp;

elseif sfading\_mode == 2

nak\_ms(cluster\_index) = m0\_sp;

end

% apply nakagami

for path = 1:path\_ix

h\_val = (gamrnd(nak\_m(path), tmp\_h(path)/nak\_m(path))).^(1/2);

tmp\_h(path) = h\_val;

end

np(k) = path\_ix; % number of rays (or paths) for this realization

[sort\_tmp\_t,sort\_ix] = sort(tmp\_t(1:np(k))); % sort in ascending time order

t(1:np(k),k) = sort\_tmp\_t;

h(1:np(k),k) = tmp\_h(sort\_ix(1:np(k)));

% now impose a log-normal shadowing on this realization

% fac = 10^(std\_shdw\*randn/20) / sqrt( h(1:np(k),k)’ \* h(1:np(k),k) );

% h(1:np(k),k) = h(1:np(k),k) \* fac;

end

return

function [hN,N] = uwb\_sv\_cnvrt\_ct\_15\_4a( h\_ct, t, np, num\_channels, ts )

% convert continuous-time channel model h\_ct to N-times oversampled discrete-time samples

% h\_ct, t, np, and num\_channels are as specified in uwb\_sv\_model

% ts is the desired time resolution

%%hN will be produced with time resolution ts /

N.

% It is up to the user to then apply any filtering and/or complex downconversion and then

% decimate by N to finally obtain an impulse response at time resolution ts.

min\_Nfs = 100; % GHz

N = max( 1, ceil(min\_Nfs\*ts) ); % N\*fs = N/ts is the intermediate sampling frequency before decimation

N = 2^nextpow2(N); % make N a power of 2 to facilitate efficient multi-stage decimation

Nfs = N / ts;

t\_max = max(t(:)); % maximum time value across all channels

h\_len = 1 + floor(t\_max \* Nfs); % number of time samples at resolution ts / N

hN = zeros(h\_len,num\_channels);

for k = 1:num\_channels

np\_k = np(k); % number of paths in this channel

t\_Nfs = 1 + floor(t(1:np\_k,k) \* Nfs); % vector of quantized time indices for this channel

for n = 1:np\_k

hN(t\_Nfs(n),k) = hN(t\_Nfs(n),k) + h\_ct(n,k);

end

end

# (informative) MATLAB script for the IEEE 802.15.4a channel model

% modified S-V channel model evaluation

%%Written by Sun Xu, Kim Chee Wee, B. Kannan & Francois Chin on 22/02/2005

clear;

no\_output\_files = 1; % non-zero: avoids writing output files of continuous-time responses

num\_channels = 100; % number of channel impulse responses to generate

randn(’state’,12); % initialize state of function for repeatability

rand(’state’,12); % initialize state of function for repeatability

cm\_num = 6; % channel model number from 1 to 8

% get channel model params based on this channel model number

[Lam,Lmean,lambda\_mode,lambda\_1,lambda\_2,beta,Gam,gamma\_0,Kgamma, ...

sigma\_cluster,nlos,gamma\_rise,gamma\_1,chi,m0,Km,sigma\_m0,sigma\_Km, ...

sfading\_mode,m0\_sp,std\_shdw,kappa,fc,fs] = uwb\_sv\_params\_15\_4a( cm\_num );

fprintf(1,[’Model Parameters\n’ ...

’ Lam = %.4f, Lmean = %.4f, lambda\_mode(FLAG) = %d\n’ ...

’ lambda\_1 = %.4f, lambda\_2 = %.4f, beta = %.4f\n’ ...

’ Gam = %.4f, gamma0 = %.4f, Kgamma = %.4f, sigma\_cluster = %.4f\n’ ...

’ nlos(FLAG) = %d, gamma\_rise = %.4f, gamma\_1 = %.4f, chi = %.4f\n’ ...

’ m0 = %.4f, Km = %.4f, sigma\_m0 = %.4f, sigma\_Km = %.4f\n’ ...

’ sfading\_mode(FLAG) = %d, m0\_sp = %.4f, std\_shdw = %.4f\n’, ...

’ kappa = %.4f, fc = %.4fGHz, fs = %.4fGHz\n’], ...

Lam,Lmean,lambda\_mode,lambda\_1,lambda\_2,beta,Gam,gamma\_0,Kgamma, ...

sigma\_cluster,nlos,gamma\_rise,gamma\_1,chi,m0,Km,sigma\_m0,sigma\_Km,...

sfading\_mode,m0\_sp,std\_shdw,kappa,fc,fs);

ts = 1/fs; % sampling frequency

% get a bunch of realizations (impulse responses)

[h\_ct,t\_ct,t0,np] = uwb\_sv\_model\_ct\_15\_4a(Lam,Lmean,lambda\_mode,lambda\_1, ...

lambda\_2,beta,Gam,gamma\_0,Kgamma,sigma\_cluster,nlos,gamma\_rise,gamma\_1, ...

chi,m0,Km,sigma\_m0,sigma\_Km,sfading\_mode,m0\_sp,std\_shdw,num\_channels,ts);

% change to complex baseband channel

h\_ct\_len = size(h\_ct, 1);

phi = zeros(h\_ct\_len, 1);

for k = 1:num\_channels

phi = rand(h\_ct\_len, 1).\*(2\*pi);

h\_ct(:,k) = h\_ct(:,k) .\* exp(phi .\* i);

end

% now reduce continuous-time result to a discrete-time result

[hN,N] = uwb\_sv\_cnvrt\_ct\_15\_4a( h\_ct, t\_ct, np, num\_channels, ts );

if N > 1,

h = resample(hN, 1, N); % decimate the columns of hN by factor N

else

h = hN;

end

% add the frequency dependency

[h]= uwb\_sv\_freq\_depend\_ct\_15\_4a(h,fc,fs,num\_channels,kappa);

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

% Testing and ploting

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

% channel energy

channel\_energy = sum(abs(h).^2);

h\_len = length(h(:,1));

t = [0:(h\_len-1)] \* ts; % for use in computing excess & RMS delays

excess\_delay = zeros(1,num\_channels);

RMS\_delay = zeros(1,num\_channels);

num\_sig\_paths = zeros(1,num\_channels);

num\_sig\_e\_paths = zeros(1,num\_channels);

for k=1:num\_channels

% determine excess delay and RMS delay

sq\_h = abs(h(:,k)).^2 / channel\_energy(k);

t\_norm = t - t0(k); % remove the randomized arrival time of first cluster

excess\_delay(k) = t\_norm \* sq\_h;

RMS\_delay(k) = sqrt( ((t\_norm-excess\_delay(k)).^2) \* sq\_h );

% determine number of significant paths (paths within 10 dB from peak)

threshold\_dB = -10; % dB

temp\_h = abs(h(:,k));

temp\_thresh = 10^(threshold\_dB/20) \* max(temp\_h);

num\_sig\_paths(k) = sum(temp\_h > temp\_thresh);

% determine number of sig. paths (captures x % of energy in channel)

x = 0.85;

temp\_sort = sort(temp\_h.^2); % sorted in ascending order of energy

cum\_energy = cumsum(temp\_sort(end:-1:1)); % cumulative energy

index\_e = min(find(cum\_energy >= x \* cum\_energy(end)));

num\_sig\_e\_paths(k) = index\_e;

end

energy\_mean = mean(10\*log10(channel\_energy));

energy\_stddev = std(10\*log10(channel\_energy));

mean\_excess\_delay = mean(excess\_delay);

mean\_RMS\_delay = mean(RMS\_delay);

mean\_sig\_paths = mean(num\_sig\_paths);

mean\_sig\_e\_paths = mean(num\_sig\_e\_paths);

fprintf(1,’Model Characteristics\n’);

fprintf(1,’ Mean delays: excess (tau\_m) = %.1f ns, RMS (tau\_rms) = %1.f\n’, ...

mean\_excess\_delay, mean\_RMS\_delay);

fprintf(1,’ # paths: NP\_10dB = %.1f, NP\_85%% = %.1f\n’, ...

mean\_sig\_paths, mean\_sig\_e\_paths);

fprintf(1,’ Channel energy: mean = %.1f dB, std deviation = %.1f dB\n’, ...

energy\_mean, energy\_stddev);

figure(1); clf; plot(t, abs(h)); grid on

title(’Impulse response realizations’)

xlabel(’Time (nS)’)

figure(2); clf; plot([1:num\_channels], excess\_delay, ’b-’, ...

[1 num\_channels], mean\_excess\_delay\*[1 1], ’r–’ );

grid on

title(’Excess delay (nS)’)

xlabel(’Channel number’)

figure(3); clf; plot([1:num\_channels], RMS\_delay, ’b-’, ...

[1 num\_channels], mean\_RMS\_delay\*[1 1], ’r–’ );

grid on

title(’RMS delay (nS)’)

xlabel(’Channel number’)

figure(4); clf; plot([1:num\_channels], num\_sig\_paths, ’b-’, ...

[1 num\_channels], mean\_sig\_paths\*[1 1], ’r–’);

grid on

title(’Number of significant paths within 10 dB of peak’)

xlabel(’Channel number’)

figure(5); clf; plot([1:num\_channels], num\_sig\_e\_paths, ’b-’, ...

[1 num\_channels], mean\_sig\_e\_paths\*[1 1], ’r–’);

grid on

title(’Number of significant paths capturing > 85% energy’)

xlabel(’Channel number’)

temp\_average\_power = sum((abs(h))’.\*(abs(h))’, 1)/num\_channels;

temp\_average\_power = temp\_average\_power/max(temp\_average\_power);

average\_decay\_profile\_dB = 10\*log10(temp\_average\_power);

threshold\_dB = -40;

above\_threshold = find(average\_decay\_profile\_dB > threshold\_dB);

ave\_t = t(above\_threshold);

apdf\_dB = average\_decay\_profile\_dB(above\_threshold);

figure(6); clf; plot(ave\_t, apdf\_dB); grid on

title(’Average Power Decay Profile’)

xlabel(’Delay (nsec)’)

ylabel(’Average power (dB)’)

if no\_output\_files,

return

end

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

%Savinge the data

%\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

%%% save continuous-time (time,value) pairs to files

save\_fn = sprintf(’cm%d\_imr’, cm\_num);

% A complete self-contained file for Matlab users

save([save\_fn ’.mat’], ’t’, ’h’,’t\_ct’, ’h\_ct’, ’t0’, ’np’, ’num\_channels’, ’cm\_num’);

% Three comma-delimited text files for non-Matlab users:

% File #1: cmX\_imr\_np.csv lists the number of paths in each realization

dlmwrite([save\_fn ’\_np.csv’], np, ’,’); % number of paths

% File #2: cmX\_imr\_ct.csv can open with Excel

% n’th pair of columns contains the (time,value) pairs for the n’th realization

% save continous time data

th\_ct = zeros(size(t\_ct,1),3\*size(t\_ct,2));

th\_ct(:,1:3:end) = t\_ct; % time

th\_ct(:,2:3:end) = abs(h\_ct); % magnitude

th\_ct(:,3:3:end) = angle(h\_ct); % phase (radians)

fid = fopen([save\_fn ’\_ct.csv’], ’w’);

if fid < 0,

error(’unable to write .csv file for impulse response, file may be open in another application’);

end

for k = 1:size(th\_ct,1)

fprintf(fid,’%.4f,%.6f,’, th\_ct(k,1:end-2));

fprintf(fid,’%.4f,%.6f\r\n’, th\_ct(k,end-1:end)); % \r\n for Windoze end-of-line

end

fclose(fid);

% File #3: cmX\_imr\_dt.csv can open with Excel

% discrete channel impulse response magnitude and phase pair realization.

% the first column is time. phase is in radians

% save discrete time data

th = zeros(size(h,1),2\*size(h,2)+1);

th(:,1) = t’; % the first column is time scale

th(:,2:2:end) = abs(h); % even columns are magnitude

th(:,3:2:end) = angle(h); % odd columns are phase

fid = fopen([save\_fn ’\_dt.csv’], ’w’);

if fid < 0,

error(’unable to write .csv file for impulse response, file may be open in another application’);

end

for k = 1:size(th,1)

fprintf(fid,’%.4f,%.6f,’, th(k,1:end-2));

fprintf(fid,’%.4f,%.6f\r\n’, th(k,end-1:end)); % \r\n for Windoze end-of-line

end

fclose(fid);

return; % end of program

function [Lam,Lmean,lambda\_mode,lambda\_1,lambda\_2,beta,Gam,gamma\_0,Kgamma, ...

sigma\_cluster,nlos,gamma\_rise,gamma\_1,chi,m0,Km,sigma\_m0,sigma\_Km, ...

sfading\_mode,m0\_sp,std\_shdw,kappa,fc,fs] = uwb\_sv\_params\_15\_4a( cm\_num )

% Written by Sun Xu, Kim Chee Wee, B. Kannan & Francois Chin on 22/02/2004

% Return modified S-V model parameters for standard UWB channel models

%————————————————————————–

% Lam Cluster arrival rate (clusters per nsec)

% Lmean Mean number of Clusters

% lambda\_mode Flag for Mixture of poission processes for ray arrival times

% 1 -> Mixture of poission processes for the ray arrival times

% 2 -> tapped delay line model

% lambda\_1 Ray arrival rate for Mixture of poisson processes (rays per nsec)

% lambda\_2 Ray arrival rate for Mixture of poisson processes (rays per nsec)

% beta Mixture probability

%————————————————————————–

% Gam Cluster decay factor (time constant, nsec)

% gamma0 Ray decay factor (time constant, nsec)

% Kgamma Time dependence of ray decay factor

% sigma\_cluster Standard deviation of normally distributed variable for cluster energy

% nlos Flag for non line of sight channel

% 0 -> LOS

% 1 -> NLOS with first arrival path starting at t ~= 0

% 2 -> NLOS with first arrival path starting at t = 0 and diffused first cluster

% gamma\_rise Ray decay factor of diffused first cluster (time constant, nsec)

% gamma\_1 Ray decay factor of diffused first cluster (time constant, nsec)

% chi Diffuse weight of diffused first cluster

%————————————————————————–

% m0 Mean of log-normal distributed nakagami-m factor

% Km Time dependence of m0

% sigma\_m0 Standard deviation of log-normal distributed nakagami-m factor

% sigma\_Km Time dependence of sigma\_m0

% sfading\_mode Flag for small-scale fading

% 0 -> All paths have same m-factor distribution

% 1 -> LOS first path has a deterministic large m-factor

% 2 -> LOS first path of each cluster has a deterministic

% large m-factor

% m0\_sp Deterministic large m-factor

%————————————————————————–

% std\_shdw Standard deviation of log-normal shadowing of entire impulse response

%————————————————————————–

% kappa Frequency dependency of the channel

%————————————————————————–

% fc Center Frequency

% fs Frequency Range

%%

modified by I2R

if cm\_num == 1, % Residential LOS

% MPC arrival

Lam = 0.047; Lmean = 3;

lambda\_mode = 1;

lambda\_1 = 1.54; lambda\_2 = 0.15; beta = 0.095;

%MPC decay

Gam = 22.61; gamma\_0 = 12.53; Kgamma = 0; sigma\_cluster = 2.75;

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.67; Km = 0; sigma\_m0 = 0.28; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN;

% Large-scale Fading – Shadowing

std\_shdw = 2.22;

% Frequency Dependence

kappa = 1.12;

fc = 6; % GHz

fs = 8; % 2 - 10 GHz

elseif cm\_num == 2, % Residential NLOS

% MPC arrival

Lam = 0.12; Lmean = 3.5;

lambda\_mode = 1;

lambda\_1 = 1.77; lambda\_2 = 0.15; beta = 0.045;

%MPC decay

Gam = 26.27; gamma\_0 = 17.5; Kgamma = 0; sigma\_cluster = 2.93;

nlos = 1;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.69; Km = 0; sigma\_m0 = 0.32; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN;

% Large-scale Fading – Shadowing

std\_shdw = 3.51;

% Frequency Dependence

kappa = 1.53;

fc = 6; % GHz

fs = 8; % 2 - 10 GHz

elseif cm\_num == 3, % Office LOS

% MPC arrival

Lam = 0.016; Lmean = 5.4;

lambda\_mode = 1;

lambda\_1 = 0.19; lambda\_2 = 2.97; beta = 0.0184;

%MPC decay

Gam = 14.6; gamma\_0 = 6.4; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.42; Km = 0; sigma\_m0 = 0.31; sigma\_Km = 0;

sfading\_mode = 2; m0\_sp = 3; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 0; %1.9;

% Frequency Dependence

kappa = 0.03;

fc = 6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 4, % Office NLOS

% MPC arrival

Lam = 0.19; Lmean = 3.1;

lambda\_mode = 1;

lambda\_1 = 0.11; lambda\_2 = 2.09; beta = 0.0096;

%MPC decay

Gam = 19.8; gamma\_0 = 11.2; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 2;

gamma\_rise = 15.21; gamma\_1 = 11.84; chi = 0.78;

% Small-scale Fading

m0 = 0.5; Km = 0; sigma\_m0 = 0.25; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 3.9;

% Frequency Dependence

kappa =0.71;

fc = 6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 5, % Outdoor LOS

% MPC arrival

Lam = 0.0448; Lmean = 13.6;

lambda\_mode = 1;

lambda\_1 = 0.13; lambda\_2 = 2.41; beta = 0.0078;

%MPC decay

Gam = 31.7; gamma\_0 = 3.7; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.77; Km = 0; sigma\_m0 = 0.78; sigma\_Km = 0;

sfading\_mode = 2; m0\_sp = 3; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 0.83;

% Frequency Dependence

kappa = 0.12;

fc = 6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 6, % Outdoor NLOS

% MPC arrival

Lam = 0.0243; Lmean = 10.5;

lambda\_mode = 1;

lambda\_1 = 0.15; lambda\_2 = 1.13; beta = 0.062;

%MPC decay

Gam = 104.7; gamma\_0 = 9.3; Kgamma = 0; sigma\_cluster = 3; % assumption

nlos = 1;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.56; Km = 0; sigma\_m0 = 0.25; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % assumption

% Large-scale Fading – Shadowing

std\_shdw = 2; % assumption

% Frequency Dependence

kappa = 0.13;

fc =6; % GHz

fs = 8; % 3 - 6 GHz

elseif cm\_num == 7, % Industrial LOS

% MPC arrival

Lam = 0.0709; Lmean = 4.75;

lambda\_mode = 2;

lambda\_1 = 1; lambda\_2 = 1; beta = 1; % dummy in this scenario

%MPC decay

Gam = 13.47; gamma\_0 = 0.615; Kgamma = 0.926; sigma\_cluster = 4.32;

nlos = 0;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN; % dummy in this scenario

% Small-scale Fading

m0 = 0.36; Km = 0; sigma\_m0 = 1.13; sigma\_Km = 0;

sfading\_mode = 1; m0\_sp = 12.99;

% Large-scale Fading – Shadowing

std\_shdw = 6;

% Frequency Dependence

kappa = -1.103;

fc = 6; % GHz

fs = 8; % 2 - 8 GHz

elseif cm\_num == 8, % Industrial NLOS

% MPC arrival

Lam = 0.089; Lmean = 1;

lambda\_mode = 2;

lambda\_1 = 1; lambda\_2 = 1; beta = 1; % dummy in this scenario

%MPC decay

Gam = 5.83; gamma\_0 = 0.3; Kgamma = 0.44; sigma\_cluster = 2.88;

nlos = 2;

gamma\_rise = 47.23; gamma\_1 = 84.15; chi = 0.99;

% Small-scale Fading

m0 = 0.3; Km = 0; sigma\_m0 = 1.15; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % m0\_sp is assumption

% Large-scale Fading – Shadowing

std\_shdw = 6;

% Frequency Dependence

kappa = -1.427;

fc = 6; % GHz

fs = 8; % 2 - 8 GHz

elseif cm\_num == 9, % Open Outdoor Environment NLOS (Fram, Snow-Covered Open Area)

% MPC arrival

Lam = 0.0305; Lmean = 3.31;

lambda\_mode = 1;

lambda\_1 = 0.0225; lambda\_2 = 1; beta = 1;

%MPC decay

Gam = 56; gamma\_0 = 0.92; Kgamma = 0; sigma\_cluster = 3; % sigma\_cluster is assumption

nlos = 1;

gamma\_rise = NaN; gamma\_1 = NaN; chi = NaN;

% Small-scale Fading

m0 = 4.1; Km = 0; sigma\_m0 = 2.5; sigma\_Km = 0;

sfading\_mode = 0; m0\_sp = NaN; % m0\_sp is assumption

% Large-scale Fading – Shadowing

std\_shdw = 3.96;

% Frequency Dependence

kappa = -1; % Kappa is assumption

fc = 6; % GHz

fs = 8; % 2 - 8 GHz

else

error(’cm\_num is wrong!!’)

end

return

function [h]= uwb\_sv\_freq\_depend\_ct\_15\_4a(h,fc,fs,num\_channels,kappa)

% This function is used to include the frequency dependency

f0 = 5; % GHz

h\_len = length(h(:,1));

f = [fc-fs/2 : fs/h\_len/2 : fc+fs/2]./f0;

f = f.^(-2\*(kappa));

f = [f(h\_len : 2\*h\_len), f(1 : h\_len-1)]’;

i = (-1)^(1/2); % complex i

for c = 1:num\_channels

% add the frequency dependency

h2 = zeros(2\*h\_len, 1);

h2(1 : h\_len) = h(:,c); % zero padding

fh2 = fft(h2);

fh2 = fh2 .\* f;

h2 = ifft(fh2);

h(:,c) = h2(1:h\_len);

% Normalize the channel energy to 1

h(:,c) = h(:,c)/sqrt(h(:,c)’ \* h(:,c) );

end

return

function [h,t,t0,np] = uwb\_sv\_model\_ct\_15\_4a(Lam,Lmean,lambda\_mode,lambda\_1, ...

lambda\_2,beta,Gam,gamma\_0,Kgamma,sigma\_cluster,nlos,gamma\_rise,gamma\_1, ...

chi,m0,Km,sigma\_m0,sigma\_Km,sfading\_mode,m0\_sp,std\_shdw,num\_channels,ts)

% Written by Sun Xu, Kim Chee Wee, B. Kannan & Francois Chin on 22/02/2005

% IEEE 802.15.4a UWB channel model for PHY proposal evaluation

% continuous-time realization of modified S-V channel model

% Input parameters:

% detailed introduction of input parameters is at uwb\_sv\_params.m

% num\_channels number of random realizations to generate

% Outputs

% h is returned as a matrix with num\_channels columns, each column

% holding a random realization of the channel model (an impulse response)

% t is organized as h, but holds the time instances (in nsec) of the paths whose

% signed amplitudes are stored in h

% t0 is the arrival time of the first cluster for each realization

% np is the number of paths for each realization.

% Thus, the k’th realization of the channel impulse response is the sequence

% of (time,value) pairs given by (t(1:np(k),k), h(1:np(k),k))

%%

modified by I2R

% initialize and precompute some things

std\_L = 1/sqrt(2\*Lam); % std dev (nsec) of cluster arrival spacing

std\_lam\_1 = 1/sqrt(2\*lambda\_1);

std\_lam\_2 = 1/sqrt(2\*lambda\_2);

% std\_lam = 1/sqrt(2\*lambda); % std dev (nsec) of ray arrival spacing

h\_len = 1000; % there must be a better estimate of # of paths than this

ngrow = 1000; % amount to grow data structure if more paths are needed

h = zeros(h\_len,num\_channels);

t = zeros(h\_len,num\_channels);

t0 = zeros(1,num\_channels);

np = zeros(1,num\_channels);

for k = 1:num\_channels % loop over number of channels

tmp\_h = zeros(size(h,1),1);

tmp\_t = zeros(size(h,1),1);

if nlos == 1,

Tc = (std\_L\*randn)^2 + (std\_L\*randn)^2; % First cluster random arrival

else

Tc = 0; % First cluster arrival occurs at time 0

end

t0(k) = Tc;

if nlos == 2 & lambda\_mode == 2

L = 1; % for industrial NLOS environment

else

L = max(1, poissrnd(Lmean)); % number of clusters

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if Kgamma ~= 0 & nlos == 0

Tcval = []; Tc\_cluster= [];

Tc\_cluster(1,1)=Tc;

for i\_Tc=2:L+1

Tc\_cluster(1,i\_Tc)= Tc\_cluster(1,i\_Tc-1)+(std\_L\*randn)^2 + (std\_L\*randn)^2;

end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

cluster\_index = zeros(1,L);

path\_ix = 0;

nak\_m = [];

for ncluster = 1:L

% Determine Ray arrivals for each cluster

Tr = 0; % first ray arrival defined to be time 0 relative to cluster

cluster\_index(ncluster) = path\_ix+1; % remember the cluster location

gamma = Kgamma\*Tc + gamma\_0; % delay dependent cluster decay time

if nlos == 2 & ncluster == 1

gamma = gamma\_1;

end

Mcluster = sigma\_cluster\*randn;

Pcluster = 10\*log10(exp(-1\*Tc/Gam))+Mcluster; % total cluster power

Pcluster = 10^(Pcluster\*0.1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if Kgamma ~= 0 & nlos == 0

Tr\_len=Tc\_cluster(1,ncluster+1)-Tc\_cluster(1,ncluster);

else

Tr\_len = 10\*gamma;

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

while (Tr < Tr\_len),

t\_val = (Tc+Tr); % time of arrival of this ray

if nlos == 2 & ncluster == 1

% equation (22)

h\_val = Pcluster\*(1-chi\*exp(-Tr/gamma\_rise))\*exp(-Tr/gamma\_1) ...

\*(gamma+gamma\_rise)/gamma/(gamma+gamma\_rise\*(1-chi));

else

% equation (19)

h\_val = Pcluster/gamma\*exp(-Tr/gamma)/(beta\*lambda\_1+(1-beta)\*lambda\_2+1);

end

path\_ix = path\_ix + 1; % row index of this ray

if path\_ix > h\_len,

% grow the output structures to handle more paths as needed

tmp\_h = [tmp\_h; zeros(ngrow,1)];

tmp\_t = [tmp\_t; zeros(ngrow,1)];

h = [h; zeros(ngrow,num\_channels)];

t = [t; zeros(ngrow,num\_channels)];

h\_len = h\_len + ngrow;

end

tmp\_h(path\_ix) = h\_val;

tmp\_t(path\_ix) = t\_val;

% if lambda\_mode == 0

% Tr = Tr + (std\_lam\*randn)^2 + (std\_lam\*randn)^2;

if lambda\_mode == 1

if rand < beta

Tr = Tr + (std\_lam\_1\*randn)^2 + (std\_lam\_1\*randn)^2;

else

Tr = Tr + (std\_lam\_2\*randn)^2 + (std\_lam\_2\*randn)^2;

end

elseif lambda\_mode == 2

Tr = Tr + ts;

else

error(’lambda mode is wrong!’)

end

% generate log-normal distributed nakagami m-factor

m\_mu = m0 - Km\*t\_val;

m\_std = sigma\_m0 - sigma\_Km\*t\_val;

nak\_m = [nak\_m, lognrnd(m\_mu, m\_std)];

end

Tc = Tc + (std\_L\*randn)^2 + (std\_L\*randn)^2;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if Kgamma ~= 0 & nlos == 0

Tc = Tc\_cluster(1,ncluster+1);

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

end

% change m value of the first multipath to be the deterministic value

if sfading\_mode == 1

nak\_ms(cluster\_index(1)) = m0\_sp;

elseif sfading\_mode == 2

nak\_ms(cluster\_index) = m0\_sp;

end

% apply nakagami

for path = 1:path\_ix

h\_val = (gamrnd(nak\_m(path), tmp\_h(path)/nak\_m(path))).^(1/2);

tmp\_h(path) = h\_val;

end

np(k) = path\_ix; % number of rays (or paths) for this realization

[sort\_tmp\_t,sort\_ix] = sort(tmp\_t(1:np(k))); % sort in ascending time order

t(1:np(k),k) = sort\_tmp\_t;

h(1:np(k),k) = tmp\_h(sort\_ix(1:np(k)));

% now impose a log-normal shadowing on this realization

% fac = 10^(std\_shdw\*randn/20) / sqrt( h(1:np(k),k)’ \* h(1:np(k),k) );

% h(1:np(k),k) = h(1:np(k),k) \* fac;

end

return

function [hN,N] = uwb\_sv\_cnvrt\_ct\_15\_4a( h\_ct, t, np, num\_channels, ts )

% convert continuous-time channel model h\_ct to N-times oversampled discrete-time samples

% h\_ct, t, np, and num\_channels are as specified in uwb\_sv\_model

% ts is the desired time resolution

%%hN will be produced with time resolution ts /

N.

% It is up to the user to then apply any filtering and/or complex downconversion and then

% decimate by N to finally obtain an impulse response at time resolution ts.

min\_Nfs = 100; % GHz

N = max( 1, ceil(min\_Nfs\*ts) ); % N\*fs = N/ts is the intermediate sampling frequency before decimation

N = 2^nextpow2(N); % make N a power of 2 to facilitate efficient multi-stage decimation

Nfs = N / ts;

t\_max = max(t(:)); % maximum time value across all channels

h\_len = 1 + floor(t\_max \* Nfs); % number of time samples at resolution ts / N

hN = zeros(h\_len,num\_channels);

for k = 1:num\_channels

np\_k = np(k); % number of paths in this channel

t\_Nfs = 1 + floor(t(1:np\_k,k) \* Nfs); % vector of quantized time indices for this channel

for n = 1:np\_k

hN(t\_Nfs(n),k) = hN(t\_Nfs(n),k) + h\_ct(n,k);

end

end

Sample code