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| Channel Models for 45 GHz WLAN Systems |
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Abstract

Description of channel models for 45 GHz Wireless Local Area Networks (WLANs) systems based on the results of experimental measurements.

**Revision History**

1. July 2013 – Initial version describing the channel models between two STAs on the table or between an AP and a STA..

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# Introduction

Wireless multiple-input multiple-output (MIMO) technology which enables increased spectral efficiency and power efficiency is being widely investigated and is being gradually adopted [1]. The millimeter-wave frequency band is considered to be a promising candidate for the new-generation WLAN because of its availability of unused wide bandwidth.

Multiple antenna technologies are being considered as a viable solution for the next generation of millimeter-wave wireless local area networks (WLAN). The use of multiple antennas offers extended range, improved reliability and higher throughputs than conventional single antenna communication systems. Multiple antenna systems can be generally separated into two main groups: smart antenna based systems and spatial multiplexing based MIMO systems.

Smart antenna based systems exploit multiple transmit and/or receive antennas to provide diversity gain in a fading environment, antenna gain and interference suppression. These gains translate into improvement of the spectral efficiency, range and reliability of wireless networks. These systems may have an array of multiple antennas only at one end of the communication link (e.g., at the transmit side, such as multiple-input single-output (MISO) systems; or at the receive side, such as single-input multiple-output (SIMO) systems; or at both ends (MIMO) systems). In MIMO systems, each transmit antenna can broadcast at the same time and in the same bandwidth an independent signal sub-stream. This corresponds to the second category of multi-antennas systems, referred to as spatial multiplexing-based MIMO systems. For example, using this technology with *n* transmit and *n* receive antennas, an *n*-fold increase in data rate can be achieved over a single antenna system [1]. This breakthrough technology appears promising in fulfilling the growing demand for future ultra-high data rate WLAN systems.

This document describes the channel models for 45 GHz WLAN systems based on the results of experimental measurements. The goal of the channel modeling is to assist 45 GHz WLAN standardization process.

The document proposes a general structure of a new channel model which takes into account important properties of 45 GHz electromagnetic waves propagation. This model is then applied to different channel modeling scenarios by using appropriate model parameters. The current revision of this document presents a detailed description and parameters of the channel model for a conference room scenario, a cubicle office room and living room scenario. The channel model allows for generating a channel realization that includes space, time, amplitude, phase, and polarization characteristics of all rays comprising this channel realization. The space characteristics of rays include azimuth and elevation angles for both transmit and receive sides.

Three basic channel modeling scenarios are proposed in accordance with the proposal for the TGaj Evaluation Methodology (EVM) document [2]. These are conference room, cubicle office room and living room scenarios.

Reference antenna models that may be applied to the generated space-time channel realizations are implemented in the channel model and described. Two types of antenna models are proposed to be used together with the channel model. These are isotropic antenna and fan-beam antenna models.

# General Characteristics of Channel Model

## Requirements for Channel Model

The following are requirements of channel models for 45 GHz WLAN systems taking into account properties of 45 GHz channels and applications of 45 GHz WLAN technology:

* Provide accurate **space-time characteristics** of the propagation channel (basic requirement) for main usage models of interest;
* Support **multiple** antennas on both TX and RX sides with no limitation on the antenna type (i.e. isotropic antenna, fan-beam antenna);
* Account for **polarization characteristics** of antennas and signals;
* Support **non-stationarity characteristics** of the propagation channel arising from people motion around the area causing time-dependent channel variations.

## General Structure of Channel Model

The current version of the document proposes a channel structure model that provides accurate space-time characteristics and supports application of any type of antenna technology. The model allows for generating channel impulse responses with and without polarization characteristics support. For the sake of description simplicity, this section first gives a structure of the channel model without polarization characteristics and then shows how the model is extended to account for polarization characteristics.

The channel impulse response function for the channel model without polarization characteristics support may be written using a general structure as:

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where:

* *h* is a generated channel impulse response.
* *t*, *ϕtx*, *θtx*, *ϕrx*, *θrx* are time and azimuth and elevation angles at the transmitter and receiver, respectively.
* *A*(*i*)and *C*(*i*)are the gain and the channel impulse response for *i*-th cluster respectively.
* *δ*(*x*)- is the Dirac delta function.
* *T*(*i*), *Φtx*(*i*), *Θtx*(*i*), *Φrx*(*i*), *Θrx*(*i*)are time-angular coordinates of *i*-th cluster.
* *α*(*i,k*) is the amplitude of the *k*-th ray of *i*-th cluster
* *τ*(*i,k*), *ϕtx*(*i,k*), *θtx*(*i,k*), *ϕrx*(*i,k*), *θrx*(*i,k*) are relative time-angular coordinates of *k*-th ray of *i*-th cluster.

The proposed channel model adopts the clustering approach with each cluster consisting of several rays closely spaced in time and angular domains. In a real environment, time and angular parameters of different clusters and rays are time-varying functions due to a non-stationary environment. However, the rate of these variations is relatively slow. The main source of non-stationarity is envisaged to be the people motion.

As it is further described in Section 2.4, support of polarization characteristics requires the channel impulse response to be a 2x2 channel matrix rather than just a scalar as in . A 2x2 matrix is required to describe the propagation channel between two orthogonal orientations of the electric field vector **E** on the transmit and receive sides.

Based on experimental results and theoretical analysis of the phenomenon, the polarization characteristics of the model were introduced at the cluster level, assuming that all rays comprising one cluster have (approximately) the same polarization characteristics. Therefore, extending the channel structure for polarization support requires changing scalar cluster gain coefficients *A*(*i*) in by 2x2 cluster polarization matrices **H**(*i*), and the channel impulse responses realization to be described by matrix **h**:

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The structure of the model for intra cluster channel impulse response *C*(*i*) is kept unchanged from . More details on support of polarization characteristics are elaborated in Section 2.4. Simulation of the channel model without support of polarization characteristics corresponds (approximately) to the case of both antennas having horizontal linear polarization as was the case in the measurement setup used to collect the data for the conference room scenario.

The same general structure of the channel model and was used for all three considered modeling scenarios. However, statistical characteristics of different time and angular parameters of the channel model are specific for each scenario. To further improve the accuracy of the propagation channel prediction, two additional channel modeling mechanisms are introduced. First, the clusters within each scenario are classified into different types (e.g. first and second order reflections from walls are different types of clusters) with specific statistical characteristics of inter cluster parameters. Second, some of parameters of individual clusters within the same cluster type are described by taking into account their statistical dependence. These approaches improve the accuracy of the propagation channel modeling. This was verified by directly comparing the channel model with experimental data and ray-tracing simulations.

## Model Development Methodology

As it follows from the proposed general model structure , , the inter cluster and intra cluster temporal and spatial parameters need to be specified to define the channel model for some scenario.

Special considerations are required to support polarization characteristics. The approach used to account for polarization impact is described in Section 2.4.

## Polarization Characteristics Support

### Polarization Impact for 45 GHz WLAN Systems

Polarization is a property of EM waves describing the orientation of electric field **E** and magnetic intensity **H** orientation in space and time. The vector **H** due to properties of EM waves can always be unambiguously found if **E** orientation and the direction of propagation are known. So the polarization properties are usually described for **E** vector only.

Due to properties of 45 GHz propagation channel, the impact of polarization characteristics is significant and is substantially higher than for below 6 GHz WLAN bands. The physical reason for the high impact of polarization characteristics is that even NLOS (reflected) signals remain strongly polarized (i.e. coupling between orthogonally polarized modes is low) and cross-polarization discrimination (XPD) is high even for NLOS signals. The polarization of signals is changed by reflections and different types of antenna polarizations provide different received signal power for various types of clusters (e.g., LOS, first-order reflection, second-order reflection). It was demonstrated that a mismatch in polarization characteristics of the transmit and receive antennas can result in a degradation of 10-20 dB. Therefore, accurate account for polarization characteristics in the 45 GHz WLAN channel models is necessary.

To support polarization impact in the channel model, polarization characteristics of antennas and polarization characteristics of the propagation channel should be introduced. An approach to introduce polarization characteristics into the 60 GHz WLAN channel models was proposed in [5]. This approach was also used as a basis for the development of the polarization model at 45 GHz used in this document. The next sections provide details of this approach.

### Antenna Polarization Properties

To develop a polarization impact mode, the description of the polarization properties of antennas should be agreed upon.

In the far field zone of the EM field radiated by the antenna, the electric vector **E** is a function of the radiation direction (defined by the azimuth angle *ϕ* and elevation angle *θ* in the reference coordinate system) and decreases as *r*-1 with increase of the distance *r*. An illustration of the transmitted **E** vector in the far field zone is shown in Figure 1.



Figure 1. Transmitted E vector in the far field zone

Vector **E** is perpendicular to the propagation direction **k** and can be decomposed into two orthogonal components: *Eθ* and *Eφ* that belong to the planes of constant *φ* and constant *θ* angles respectively. Knowledge of *Eθ* and *Eφ* of the radiated signal (which may be functions of *φ* and *θ*) fully describes polarization characteristics of the antenna in the far field zone.

### Polarization Properties Description Using Jones Vector

Wave polarization can be described using *Jones calculus* introduced in optics for description of the polarized light. In the general case, a Jones vector is composed from two components of the electric field of the EM wave. The Jones vector **e** is defined as the normalized two-dimensional electrical field vector **E**. The first element of the Jones vector may be reduced to a real number. The second element of this vector is complex and, in the general case, defines phase difference between orthogonal components of the **E** field.

For antenna polarization model used in this document, the orthogonal components of Jones vector are defined for *Eθ* and *Eφ* components respectively. Examples of antennas polarization description using Jones vector are shown in Table 1.

Table 1. Examples of antennas polarization description using Jones vector

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| --- | --- |
| **Antenna polarization type** | **Corresponding Jones vector** |
| Linear polarized in the *θ*-direction |  |
| Linear polarized in the *φ*-direction |  |
| Left hand circular polarized (LHCP) |  |
| Right hand circular polarized (RHCP) |  |

### Polarization Characteristics of Propagation Channel

With the selected **E** field bases (*Eθ* and *Eφ* components) for the TX and RX antennas, the polarization characteristics of each ray of the propagation channel may be described by channel polarization matrix **H**.

In this case, the transmission equation for a single ray channel may be written as:

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where *x* and *y* are the transmitted and received signals, **e***TX* and **e***RX* are the polarization (Jones) vectors for the TX and RX antennas respectively. Components of polarization matrix **H** define gain coefficients between the *Eθ* and *Eφ* components at the TX and RX antennas.

For the LOS signal path, matrix **H***LOS* is close to the identity matrix (non-diagonal components may be non-zero but significantly smaller than diagonal elements) multiplied by the corresponding gain coefficient due to path loss. LOS propagation does not change polarization characteristics of the signals. However, polarization characteristics of the signals are changed upon reflections. The change of the polarization characteristics upon reflection is defined by the type of the surface and the incident angle. Thus, polarization characteristics may be different for different clusters but are similar for the rays comprising one cluster. For this reason, the polarization impact was modeled at the cluster level with all rays inside one cluster having the same polarization properties. Modeling polarization impact at the level of individual rays would unnecessary complicate the model and would not provide any essential increase of the model accuracy. Account for polarization at the cluster level is included in the general structure of the model with polarization characteristics support given in .

### Polarization Channel Matrix for First and Second Order Reflections

It is known that reflection coefficients are different for **E** field components parallel and perpendicular to the plane of incidence and depend on the incident angle. Theoretical coupling between parallel and perpendicular components of the reflected signal is zero for plane media interfaces (boundaries). But due to non-idealities (roughness) of the surfaces some coupling always exists in the real channels.

An example of a first order reflected signal path is shown in Figure 2.



Figure 2. First order reflected signal path

The polarization matrix for the first order reflected signal path may be found as a product of the matrix that rotates **E** vector components from the coordinate system associated with the TX antenna to the coordinate system associated with the incident plane. Next, reflection matrix **R** with reflection coefficients and cross-polarization coupling coefficients is applied, followed by a rotation to the coordinate system associated with the RX antenna. Thus, the channel propagation matrix for the case of the first order reflected signals may be defined as:

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The reflection matrix **R** includes the reflection coefficients *R*⊥ and *R*|| for the perpendicular and parallel components of the electric field *E* ⊥and *E* || respectively. Elements *ξ*1 and *ξ*2 in the matrix **R** are cross-polarization coupling coefficients.

Note that the structure of matrix **H** given in does not include the propagation loss along the corresponding reflected path, which should be taken into account in the final model, but does not impact polarization properties.

Similar to , the structure of polarization matrix **H** for a second order reflection is given in and includes additional rotation and reflection matrices.

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Note that in general case the first incident plane dose not coincide with the second incident plane. Therefore the additional recalculation from coordinate system associated with the first incident plane to the coordinate system associated with the second incident plane is required.

To obtain statistical models for different types of reflected clusters, the following methodology was proposed. First, (statistical) models for the elements of the reflection matrix **R** are defined. This may be accomplished by using available experimental data or theoretical Fresnel formulas. Then ray-tracing of interesting environments (conference room, cubicle environment, and living room) is performed with taking into account geometry and polarization characteristics of the propagation channel. After that multiple realizations of the channel polarization matrices **H** for different types of clusters are found and their statistical models are derived by approximation of the calculated empirical distributions.

Note that there are generally two mechanisms for depolarization (coupling between orthogonal components of the **E** vector at the TX and RX sides). These are reflection coupling (coupling between parallel and perpendicular **E** vector components at the reflection) and geometrical coupling (coupling because of the different relative orientations of the TX and RX antennas). It may be seen that the proposed approach allows accounting for both mechanisms to create an accurate polarization impact model.

## Usage of Channel Model in Simulations

This subsection gives a brief description of the channel realization generation process that is implemented in the channel model. The whole process of the channel realization generation is schematically shown in Figure 3.



Figure 3. Process of channel realization generation

The generation of the channel impulse response begins with selecting model input parameters.

The next step is generation of all possible channel clusters between the transmitter and receiver. Amplitude, time, and angular and polarization characteristics for all clusters are generated.

In a real environment not all the clusters are available for communications, some of the clusters are blocked by people, furniture, and other objects. To take this into account, a part of the clusters is blocked in the channel model. The blocked part of the clusters is selected randomly. Each cluster has an individual probability of being blocked. This probability is independent from the blockage probabilities of other clusters.

After a subset of non-blocked clusters is defined the intra cluster parameters for each non-blocked cluster are generated. Each cluster consists of multiple rays and the output of this step includes amplitude, phase, time, and angular parameters for all rays of the given channel realization. After this step the generation of channel realization is completed. But in order to be used a simulation, antenna models must be applied to the generated realization and it must be converted from continuous to discrete time.

Reference antenna models and MIMO correlation matrix are included, which may be applied in the next step of the channel realization generation process.

In the last step the channel impulse are converted from continuous time to discrete time with the specified sample. After this step the generation of the discrete time MIMO channel impulse responses are completed and useable in simulations.

# Conference Room Channel Model

## Measurements and Modeling Scenarios

The channel model for the conference room environment is based on the experimental results.

## Model Development Methodology

This section describes the methodology used to develop a channel model for the conference room environment.

## Inter Cluster Parameters for STA-STA Sub-scenario

This section gives description of the statistical models for inter cluster parameters of the STA-STA sub-scenario.

### LOS Ray

The first type of cluster is the LOS path, which is modeled as a single ray with the gain equal to:

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where *λ* is a wavelength, and *d* is a separation between TX and RX. Parameters *λ* and *d* are input parameters of the channel model.

Relationship **错误!未找到引用源。** is derived from the Friis transmission equation, which sets the signal receive power P*rx* as:

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where *Gtx* and *Grx* are TX and RX antennas gains respectively and *Ptx* is the transmitted power. The antenna gain coefficients are taken into account when an antenna model is applied and so the LOS amplitude gain is given by **错误!未找到引用源。**.

The LOS component has zero TX and RX azimuth and elevation angles and also zero time of arrival (TOA). The TX and RX elevation and azimuth angles, as well as times for arrival for other clusters, are defined relatively to the LOS path in the STA-STA sub-scenario.

### Time of Arrival Distribution for Different NLOS Clusters

TOA of different clusters is calculated relatively to the LOS path time of arrival. Empirical distributions of the TOA for different cluster groups have been obtained by ray tracing simulations. Then piecewise linear approximations of the empirical probability density functions (PDFs) were used to develop statistical models for the TOA parameters.

### Angular Characteristics for First Order Reflection from Walls

### Angular Characteristics for First Order Reflections from Ceiling

A single cluster corresponding to the 1st order reflection from the ceiling takes into account the following properties:

* all azimuth angles are equal to zero;
* elevation angles for TX and RX are equal to each other.

### Angular Characteristics for Second Order Reflections from Walls and Ceiling

The model for the second order reflections from walls and ceiling take into account the following properties:

* There are in total four second order clusters corresponding to reflection from wall and then ceiling or from ceiling and then wall for the chosen distributions of TX and RX positions.
* There is always exactly one reflection for each wall (either wall and then ceiling or ceiling and then wall).
* The azimuth angles for these clusters are equal to the azimuth angles of the clusters from first order reflections from walls.
* The elevation angles of the same cluster are equal for TX and RX.

### Angular Characteristics for Second Order Reflections from Walls

This group of clusters has the following main properties:

* There are in total eight clusters corresponding to the second order reflections from walls.
* These clusters have elevation angles equal to zero.
* The TX azimuth angles for these clusters are equal to either the RX azimuth angle or RX azimuth angle +/– 1800.
* There are four regions in the joint distribution of TX and RX azimuth angles and there are always two clusters in each region.

### Gain of Clusters

As it was mentioned above the gain for LOS is predicted by the Friis transmission equation (or free space propagation law). For NLOS first and second order reflected clusters the gain is calculated as:

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where *g*(*i*) is a reflection loss, *λ* is a wavelength (6.7 mm), *d* is a distance between TX and RX (along LOS path), *R* is a total distance along the cluster path decreased by *d*, *R* is calculated as a product of TOA relatively LOS and the speed of light.

### Model of Dynamical Human Blockage

In a real environment not all clusters that occur in an empty conference room may be used for communication. Part of the clusters may be blocked by people sitting or moving in the conference room and also by other objects. This effect is taken into account in the channel model by the introduction of the cluster blockage probability associated with each type of cluster. In reality, different objects and people blocking signal propagation paths may have more complicated effect on the channel structure. For example, additional reflected clusters may appear. But, in order to keep the channel model complexity low, this effect was modeled by simple human induced cluster blockage.

## Polarization Impact Modeling for STA-STA Sub-scenario

### Polarization Impact Model Development

Section 2.4 described the approach that is proposed for developing polarization impact model. In this approach, the ray-tracing simulations accounting for polarization impact are used to generate empirical distributions of cluster polarization matrices and these distributions are then approximated to create statistical models. However, the unsolved problem in Section 2.4 was how to define coefficients of the reflection matrix **R** (needed to simulate reflections in ray-tracing):

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where *R*⊥ and *R*|| are reflection coefficients for perpendicular and parallel (relatively to the plane of incidence) components of the **E** vector and *ξ*1 and *ξ*2 are cross-coupling coefficients.

This section describes the approach adopted for the reflection matrix **R** modeling in the conference room scenario. The next sections use this approach to develop statistical models for the cluster polarization matrices **H**.

Development of a statistical model for the **R** matrix can be divided into two separate tasks of first finding models for the diagonal coefficients *R*⊥ and *R*|| and then for the non-diagonal cross-coupling coefficients *ξ*1 and *ξ*2. The cross-coupling coefficients *ξ*1 and *ξ*2 are equal to zero for reflections from the ideal flat media interface and though these coefficients are non-zero for reflections from real surfaces, their values are significantly below than for the *R*⊥ and *R*|| coefficients. Therefore, accurate prediction of the diagonal coefficients is much more important for developing an overall accurate model.

One simple approach to create a model for the diagonal *R*⊥ and *R*|| coefficients may be to use Fresnel formulas providing the laws of reflection coefficients vs. incident angle dependence for parallel and perpendicular reflection coefficients *R*⊥ and *R*|| for the flat interface between regions with the refraction indices *n*1 and *n*2:

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where α*inc* is the incident angle.

The next sections describe statistical models developed for the polarization matrix **H** of different types of clusters of the STA-STA sub-scenario.

### Polarization Characteristics of LOS Ray

Polarization characteristics of the LOS ray are modeled by the polarization matrix **H***LOS*:

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The polarization characteristics of the signal are not altered by the free space propagation. Hence in the general case, the polarization matrix **H***LOS* will be a rotation matrix of transformation between the polarization bases of the TX and RX antennas. In the conference room channel model, the polarization bases of the TX and RX antennas are the same and the rotation matrix is reduced to the identity matrix.

For the sake of description simplicity, the matrix **H** given in does not include the propagation loss factor that should be additionally applied in the simulations as it is described in Section 3.3.1.

### Polarization Characteristics of First Order Reflections from Walls

For first order reflections from walls, multiple realizations of the polarization matrix **H** were obtained with the ray-tracing using the methodology proposed in Section 2.4 and Section 3.4.1.

### Polarization Characteristics of First Order Reflections from Ceiling

Multiple realizations were generated with the help of ray-tracing for the polarization matrix **H** for the first order reflected cluster from ceiling.

The described approximations of the matrix **H** account for the loss of the signal power due to reflection but do not account for the propagation loss that should be included in the simulation model as it is described in Section 3.3.7.

### Polarization Characteristics of Second Order Reflections from Walls and Ceiling

To generate polarization matrices realizations for the second order reflections from walls and ceiling, the methodology described in Section 3.4.1 was used.

### Statistical Properties of Reflection Loss Coefficients for Different TX and RX Antennas Polarizations and Different Types of Clusters

As explained in Sections 2.4, 3.3.7, and 3.4, the reflection loss coefficient of cluster depends on its polarization and polarization characteristics of the used antennas. The statistical models of the reflection loss coefficients presented in Section 3.3.7 for the first and second order clusters types are developed in assumption that TX and RX antennas have linear horizontal (vertical) polarization. To obtain reflection loss distributions for an arbitrary configuration of TX and RX antennas polarizations the models of polarization matrices for different types of clusters developed in Sections 3.4.3 - **错误!未找到引用源。** need to be used. This section presents statistical characteristics of reflection loss coefficients for different antennas polarizations and different types of clusters.

In general case, a reflection loss coefficient for a single cluster may be written as follows

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where **e***TX* and **e***RX* are the polarization (Jones) vectors for the TX and RX antennas respectively, **H** is a cluster polarization matrix.

## Inter Cluster Parameters for STA-AP Sub-scenario

This section describes statistical models for the inter cluster parameters of the STA-AP sub-scenario.

### LOS Ray

The LOS ray modeling is similar to the approach used for the STA-STA sub-scenario (see Section 3.3.1 for details).

There is a difference in the introduction of the coordinate system and calculation of the azimuth angles between the STA-STA and STA-AP sub-scenarios. For the STA-STA sub-scenario, the coordinate system is introduced so that the zero elevation angle plane is the horizontal plane of the room and the zero azimuth angle plane is the vertical plane including the LOS path. In this case, the LOS direction has zero azimuth and elevation angles of arrival and departure. For the STA-AP sub-scenario, the coordinate system is also introduced so that the zero elevation angle plane is the horizontal plane of the room and the zero azimuth angle plane is the vertical plane including the LOS path. However for the STA-AP sub-scenario, this results in the LOS path having zero azimuth angle but non-zero elevation angle. The azimuth and elevation angles for other types of clusters are calculated in the same coordinate system, and the elevation angles of other clusters cannot be considered as calculated relatively to the LOS path.

### Time of Arrival (TOA) Distribution for Different NLOS Clusters

There are two types of NLOS clusters for the STA-AP sub-scenario: first order reflected clusters from walls and second order reflected clusters from walls.

The same approach as for the STA-STA sub-scenario was used for modeling TOA of NLOS clusters in the STA-AP sub-scenario. TOA of different clusters is calculated relatively to the LOS path time of arrival. Empirical distributions of the TOA for different cluster group are obtained by ray tracing simulations. Then piecewise linear approximations of the empirical probability density functions (PDFs) are used to develop statistical models for the TOA parameters.

### Distribution of Azimuth Angles for First Order Reflected Clusters from Walls

The same modeling approach as in the STA-STA sub-scenario (see Section 3.3.3 for details) was used to define statistical models of azimuth angles for the four first order reflected clusters in the STA-AP sub-scenario.

### Distribution of Azimuth Angles for Second Order Reflected Clusters from Walls

The modeling approach for predicting azimuth angles for the second order reflections from walls is the same as for the STA-STA sub-scenario (see Section 3.3.6 for details).

### Distribution of Elevation Angles for First and Second Order Reflections

For the STA-AP sub-scenario, statistical models are required to generate elevation angles realizations for all three types of clusters: the LOS ray, the first order reflections from walls, and the second order reflections from walls, because the STA and the AP are placed at different heights. For a single cluster of any type, the elevation angles at the STA and AP have the same absolute values but different signs – positive for the STA and negative for the AP.

### Gain of Clusters

The simulation of clusters gain is the same as for the STA-STA sub-scenario (see Section 3.3.7 for details).

### Model of Dynamical Human Blockage

As it is discussed in Section 3.3.8, not all the clusters present in the empty conference may be available for establishing a communication link. Some clusters may be blocked by people sitting, standing, or moving around in the conference room. This effect is modeled by cluster blockage that happens with some probability. This probability is different for different groups of clusters. For the STA-AP sub-scenario the same methodology has been used to derive the probabilities of Cluster Blockage than for the STA-STA scenario (see Section 3.3.8).

## Polarization Impact Modeling for STA-AP Sub-scenario

Polarization impact modeling for the STA-AP sub-scenario adopts the same methodology as for the STA-STA sub-scenario (see Section 2.4 and Section 3.4.1 for a comprehensive description).

### Polarization Characteristics of LOS Ray

The polarization modeling for the LOS ray is the same as for the STA-STA sub-scenario (see Section 3.4.2 for details).

### Polarization Characteristics of First Order Reflections from Walls

### Polarization Characteristics of Second Order Reflections from Walls

### Statistical Properties of Reflection Loss Coefficients for Different TX and RX Antennas Polarizations and Different Types of Clusters

This section presents statistical characteristics of reflection loss coefficients for different antennas polarizations and different types of clusters.

## Intra Cluster Parameters

In accordance with equation the structure of the *i*-th cluster of the channel is written as:

|  |  |
| --- | --- |
|  |  |

where *α*(*i,k*) is the amplitude of the *k*-th ray of *i*-th cluster and *τ*(*i,k*), *ϕtx*(*i,k*), *θtx*(*i,k*), *ϕrx*(*i,k*), *θrx*(*i,k*) are relative time-angular coordinates of *k*-th ray of *i*-th cluster.

# Channel Model for Cubicle Environment

## Modelling Scenario

## Model Development Methodology

This section describes the methodology used to develop a channel model for the enterprise cubicle environment.

To define inter cluster parameters for the cubicle scenario, a similar methodology to the one for the conference room channel development (see Section 3.2) was applied. A ray tracing model of the cubicle environment has been used to generate multiple realizations of 1st order and one 2nd order reflections. Then, similar to the conference room scenario, statistical time and angular characteristics of the 1st order and 2nd order reflections were calculated from ray tracing simulations results and then used to derive the corresponding inter cluster time and angular parameters for the enterprise cubicle channel model.

For the ray tracing simulations, positions of the transmitting (AP) and receiving (laptop) devices were taken as described in the EVM and modeling scenario defined in Section 4.1. AP was taken to be located at the height of 2.9 m above the floor and had the fixed position. Laptop was taken to be located at the table surface in random positions. It was assumed that antenna may be placed in laptop lid and therefore have some altitude above the table plane. This allows to see the 1st order cluster reflected from the table. Therefore laptop was randomly placed in the flat layer with the height equal to 0.9 m above the floor (0.2 m above the table plane) and the horizontal dimensions limited by the table edges. Positions of the laptop were distributed uniformly within this layer.

## Inter Cluster Parameters

This section gives description of the statistical models for inter-cluster parameters for the enterprise cubicle environment.

### LOS Ray

The LOS ray modelling is similar to the approach introduced for the CR scenario. For more details, see Section 3.3.1.

### Time of Arrival Distribution for Different NLOS Clusters

TOA of different clusters is calculated relatively to the LOS path time of arrival. Empirical distributions of the TOA for different clusters have been obtained by ray tracing simulations. Then approximations of the empirical probability density functions (PDFs) were used to develop statistical models for the TOA parameters.

### Angular Characteristics for NLOS Clusters

### Gain of Clusters

The approach of using Friis transmission equation for modeling propagation loss for the LOS path, 1st order reflected clusters, and 2nd order reflected clusters is same as described in 3.3.7.

## Polarization Impact Modelling

Polarization modeling for enterprise cubicle environment adopts the same methodology as for the conference room STA-STA sub-scenario (see Section 2.4 and Section 3.4.1 for a comprehensive description).

### Polarization Characteristics of LOS Ray

The polarization modelling for the LOS ray is the same as for the conference room STA-STA sub-scenario (see Section 3.4.2 for details).

### Polarization Characteristics of First Order Reflections from Office Walls

### Polarization Characteristics of First Order Reflections from Cubicle Walls

### Polarization Characteristics of First Order Reflection from Table

### Polarization Characteristics of Second Order Reflection from Table and Ceiling

### Statistical Properties of Reflection Loss Coefficients for Different TX and RX Antennas Polarizations and Different Types of Clusters

This section presents statistical characteristics of reflection loss coefficients for different antennas polarizations and different types of clusters. The same approach is used to obtain distributions of reflection loss coefficients as described in Section 3.4.6.

## Intra Cluster Parameters

# Living Room Channel Model

## Modelling Scenario

Home living room is one of the three simulation scenarios defined by the EVM [2].

## Model Development Methodology

This section describes the methodology used to develop a channel model for the home living room environment.

## Inter Cluster Parameters

This section gives description of the statistical models for inter-cluster parameters for the home living room environment.

### LOS Ray

The LOS ray modelling is similar to the approach introduced for the CR STA-STA sub-scenario. For more details, see Section 3.3.1.

### Time of Arrival Distribution for Different NLOS Clusters

TOA of different clusters is calculated relatively to the LOS path time of arrival. Empirical distributions of the TOA for different cluster groups have been obtained by ray tracing simulations. Then piecewise linear approximations of the empirical probability density functions (PDFs) were used to develop statistical models for the TOA parameters.

### Angular Characteristics for First Order Reflection from Walls

### Angular Characteristics for First Order Reflections from Ceiling and Floor

### Angular Characteristics for Second Order Reflections from Walls

This group of clusters has the following main properties:

* There are total 5 clusters corresponding to the second order reflections from walls
* These clusters have elevation angles equal to zero
* The RX azimuth angles for these clusters are equal to either the TX azimuth angle or TX azimuth angle +/- 1800.

### Angular Characteristics for Second Order Reflections from Ceiling and Floor

There are two clusters corresponding to second order reflections from ceiling and floor. Generation of these clusters takes into account the following properties:

* Azimuth angles for these clusters are equal to zero for TX and RX
* Elevation angles for ceiling-floor (or floor-ceiling) reflection have equal absolute values and opposite signs at the TX and RX sides
* Elevation angles for ceiling-floor and floor-ceiling reflections have equal absolute values and opposite signs at either TX or RX sides

### Angular Characteristics for Second Order Reflections from Walls and Ceiling (from Walls and Floor)

### Gain of Clusters

The simulation of clusters gain is the same as for the conference room STA-STA sub-scenario (see Section 3.3.7 for details).

### Probabilities of Clusters Blockage

## Polarization Impact Modelling

Polarization impact modelling for living room environment adopts the same methodology as for the conference room STA-STA sub-scenario (see Section 2.4 and Section 3.4.1 for a comprehensive description).

### Polarization Characteristics of LOS Ray

The polarization modelling for the LOS ray is the same as for the conference room STA-STA sub-scenario (see Section 3.4.2 for details).

### Polarization Characteristics of First Order Reflections from Walls

### Polarization Characteristics of Second Order Reflections from Walls

### Polarization Characteristics of Second Order Reflections from Ceiling and Floor

### Polarization Characteristics of Second Order reflections from Walls and Ceiling (Floor)

### Statistical Properties of Reflection Loss Coefficients for Different TX and RX Antennas Polarizations and Different Types of Clusters

## Intra Cluster Parameters

For modelling intra cluster distributions the same approach developed in Section 3.7 for conference room environment is applied.

# Antenna Models

This section provides a description of reference antenna models that may be used together with the channel model. The reference antenna models were developed to demonstrate the application of the channel model in simulations of 45 GHz communication systems with steerable directional antennas.

Two antenna models are developed together with the given channel model. These are isotropic radiator, fan-beam antenna. Different types of antenna models with different parameters (e.g. beamwidths) may be used in the simulations. The two developed antenna models capture most of the practical simulation scenarios. However, the channel model is not limited in this sense and any additional antenna models may be created.

The support of polarization characteristics for antennas was introduced in Section 2.4.2. The polarization characteristics are directly supported for the basic steerable antenna model. Polarization characteristics are not supported in the isotropic radiator model because these two concepts are incompatible. Introduction of any polarization characteristics will give rise to spatial radiation selectivity of the isotropic radiator. For the antenna array, the polarization characteristics are also not supported in this version of the document, because the only introduced type of the elementary radiator is the isotropic radiator, which does not support polarization characteristics. Therefore, only basic steerable antenna model may be currently used in the simulations with polarization impact modeling.

## Application of Transmit and Receive Antennas to Channel Model

Analytical description for channel impulse response functions without and with polarization characteristics support were introduced in Section 2.2 (equations and correspondingly). These equations define a channel impulse response in the space-time domain.

Application of antennas at the TX and RX sides is equivalent to spatial filtering procedure. The channel impulse response after application of TX and RX antennas depends only on the signal time of arrival.

If polarization characteristics for TX and RX antennas are not considered, then application of TX and RX antenna patterns to the channel impulse response described by equation is given as follows:

 

where g*TX*(*φ, θ*) and g*RX*(*φ, θ*) are antenna gain functions (antenna patterns) for TX and RX antennas respectively. In the case of the isotropic radiator antenna, the gain function is a constant value for all space directions and does not depend on azimuth and elevation angles. Therefore, the channel impulse response includes all rays existing between TX and RX sides. In the common case of steerable directional antenna, g(*φ, θ*) is a function of azimuth and elevation angles, therefore, some rays are sufficiently attenuated while others are amplified depending on their spatial position.

If polarization properties of TX and RX antennas are taken into account, then application of TX and RX antenna patterns to the channel impulse response described by equation is given as follows

 

where  and  are antenna gain functions (supporting polarization characteristics) for TX and RX antennas respectively.

Note that the antenna gain function  is changed when antenna changes its spatial orientation. Therefore, the channel impulse response also depends on the antenna pattern spatial orientation.

## Isotropic Radiator

The simplest type of the antenna model is an isotropic radiator [6]. This model has a spherical antenna pattern that equally illuminates all signal rays at the transmitter and equally combines all rays coming from different directions at the receiver.

The isotopic antenna cannot be implemented in practice but is a convenient theoretical model which is used in the channel model for analytical purposes.

## Fan-Beam Radiator

The second type of the antenna model is a fan-beam radiator. This model has a fan antenna pattern that illuminates signal rays in a fan shape area at the transmitter and combines all rays coming from a given fan shape area at the receiver.

# MIMO Matrix Formulation

We follow the MIMO modeling approach presented in [10], [11] that utilizes receive and transmit correlation matrices. The MIMO channel matrix *H* for each tap, at one instance of time, in the A-F delay profile models can be separated into a fixed (constant, LOS) matrix and a Rayleigh (variable, NLOS) matrix (4 transmit and 4 receive antennas example)

 

where *Xij* (*i*-th receiving and *j*-th transmitting antenna) are correlated zero-mean, unit variance, complex Gaussian random variables as coefficients of the variable NLOS (Rayleigh) matrix *HV*, exp(*jij*) are the elements of the fixed LOS matrix *HF*, *K* is the Ricean *K*-factor, and *P* is the power of each tap. We assume that each tap consists of a number of individual rays so that the complex Gaussian assumption is valid. *P* in (3) represents the sum of the fixed LOS power and the variable NLOS power (sum of powers of all taps).

To correlate the *Xij* elements of the matrix *X*, the following method can be used

 

where *Rtx* and *Rrx* are the receive and transmit correlation matrices, respectively, and *Hiid* is a matrix of independent zero mean, unit variance, complex Gaussian random variables, and

 

where  are the complex correlation coefficients between *i*-th and *j*-th transmitting antennas, and  are the complex correlation coefficients between *i*-th and *j*-th receiving antennas. An alternative approach uses the *Kronecker* product of the transmit and receive correlation matrices (*Hiid* is an array in this case instead of matrix)

 

**Following is an example of 4 x 4 MIMO channel transmit and receive correlation matrices**  

The complex correlation coefficient values calculation for each tap is based on the power angular spectrum (PAS) with angular spread (AS) being the second moment of PAS [12], [13]. Using the PAS shape, AS, mean angle-of-arrival (AoA), and individual tap powers, correlation matrices of each tap can be determined as described in [13]. For the uniform linear array (ULA) the complex correlation coefficient at the linear antenna array is expressed as

 

where , and *RXX* and *RXY* are the cross-correlation functions between the real parts (equal to the cross-correlation function between the imaginary parts) and between the real part and imaginary part, respectively, with

 

and

 

Expressions for correlation coefficients assuming uniform, truncated Gaussian, and truncated Laplacian PAS shapes can be found in [13]. To calculate the numerical values of correlation matrices we use a Matlab program developed and distributed by L. Schumacher [14] (see Sec. 6).

Next we briefly describe the various steps in our cluster modeling approach. We

* Start with delay profiles of models B-F.
* Manually identify clusters in each of the five models.
* Extend clusters so that they overlap, determine tap powers (see Appendix A).
* Assume PAS shape of each cluster and corresponding taps (Laplacian).
* Assign AS to each cluster and corresponding taps.
* Assign mean AoA (AoD) to each cluster and corresponding taps.
* Assume antenna configuration.
* Calculate correlation matrices for each tap.

# Path Loss

## Path Loss Modeling

Sections 2 – 4.1 provide description of the general structure of the 45 GHz WLAN channel models and procedures proposed for the generation of the channel model parameters that are specific for different evaluation scenarios.

The developed channel models provide complex amplitudes of different rays taking into account the attenuation of the signal between the transmitter and receiver along the rays in a real scale. Hence, each ray has a part of information about the propagation loss of the channel and a part of information about the impulse response.

Note that this approach is different from a traditional channel modeling approach in the WLAN bands of 2.4 and 5 GHz where separate models are generated for path loss and channel impulse response. In 2.4 GHz and 5 GHz bands most of the channel rays contribute to the total received signal power even if multiple antennas are used and spatial signal processing algorithms are applied. Thus, the separation between path loss and impulse response models is possible and the path loss function describes average energy (power) behavior of electromagnetic field for different distances and the channel impulse response function independently describes channel realization behavior.

## Path Loss Model for Conference Room

This section presents path loss models for the conference room STA-STA and STA-AP sub-scenarios for LOS and NLOS propagation environments.

## Path Loss Model for Cubicle Environment

This section presents path loss model for the enterprise cubicle for LOS and NLOS propagation environments.

## Path Loss Model for Living Room

This section presents path loss model for the living room for LOS and NLOS propagation environments. Isotropic TX to directional RX and directional TX to directional RX antennas configurations are used to develop path loss model for both LOS and NLOS propagation environments.

## Path Loss Model Summary

The characteristics of the 45 GHz WLAN propagation channel complicate the development of the independent path loss model. However, if antenna system parameters are fixed then it is possible to derive an average path loss model using the standard form:

|  |  |
| --- | --- |
| . |  |

Here *A* and *n* are parameters specific for the scenario and antenna system, *f* is the carrier frequency in GHz, *R* is the distance between TX and RX in m.

# Dynamic Model for System Level Simulations with MAC Protocols

This section gives guidelines how to include channel dynamics due to human movement that may be included in system level simulations with MAC protocols.

The dynamical human blockage model considered in Sections 3.3.8 and 3.5.7 uses the assumption that channel realizations are generated independently for random time instances, meaning the temporal characteristics of shadowing events are not included. This simplification is valid only for PHY level simulations. In this case no correlation between successive generated impulse responses is required, since PHY level simulations assume averaging over a large number of channel realizations. In order to cover the influence of human induced channel dynamics, both temporal characteristics and signal level/SNR degradation has to be considered in system level simulations that include MAC protocols. Therefore, a statistical model needs to be developed.

Table 2. Human induced shadow fading model parameters

|  |  |
| --- | --- |
| **Parameter** | **Distribution**  |
| *tD[s]* | Weibull ( = , *k* = ) |
| *tdecay,3dB[s]* | Weibull(** = , *k* = ) |
| *trise,3dB[s]* | Weibull (** = , *k* =) |
| *Amean[dB]* | Gaussian (** = , ** =) |

# References

1. G.J. Foschini and M.J. Gans, “On the limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Personal Communications*, vol. 6, March 1998, pp. 311-335.
2. IEEE doc. 802.11-12/1382r2. IEEE 802.11aj Evaluation Methodology, X. M. Peng *et al.*, Apr. 24, 2013.
3. IEEE doc. 802.11-03/940r4, TGn channel models, V. Erceg *et al.*, May 5, 2004.
4. IEEE doc. 802.11-09/0334r8, Channel models for 60 GHz WLAN systems, A. Maltsev *et al.*, May 20, 2010.
5. IEEE doc. 802.11-09/0431r0. Polarization model for 60 GHz, A. Maltsev *et al*, April 2, 2009.
6. IEEE Std 145-1993. *IEEE Standard Definitions of Terms for Antennas*, March 18, 1993
7. Spatial channel model text description, SCM text v.7.0, Spatial channel model AHG (combined ad-hoc from 3GPP&3GPPs), Aug. 19, 2003.
8. C.A. Balanis, *Antenna Theory*. New Jersey: Wiley, 2005.
9. M. J. Lee, I. Song, S. Yoon, and S. R. Par, “Evaluation of directivity for planar antenna arrays,” IEEE Antennas Propagat. Mag., vol. 42, no. 3, June 2000
10. J.P. Kermoal, L. Schumacher, P.E. Mogensen and K.I. Pedersen, “Experimental investigation of correlation properties of MIMO radio channels for indoor picocell scenario,” in *Proc. IEEE Veh. Technol. Conf.*, Boston, USA, vol. 1, Sept. 2000, pp. 14-21.
11. L. Schumacher, K. I. Pedersen, and P.E. Mogensen, “From antenna spacings to theoretical capacities – guidelines for simulating MIMO systems,” in *Proc. PIMRC Conf.*, vol. 2, Sept. 2002, pp. 587-592.
12. J. Salz and J.H. Winters, “Effect of fading correlation on adaptive arrays in digital mobile radio,” *IEEE Trans. Veh. Technol.*, vol. 43, Nov. 1994, pp. 1049-1057.
13. L. Schumacher, K. I. Pedersen, and P.E. Mogensen, “From antenna spacings to theoretical capacities – guidelines for simulating MIMO systems,” in *Proc. PIMRC Conf.*, vol. 2, Sept. 2002, pp. 587-592.
14. L. Schumacher “WLAN MIMO Channel Matlab program,” download information: http://www.info.fundp.ac.be/~lsc/Research/IEEE\_80211\_HTSG\_CMSC/distribution\_terms.html