P802.11  
Wireless LANs

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| Channel Models for IEEE 802.11ay | | | | |
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Abstract

This document is an amendment to the “Channel Models for 60 GHz WLAN Systems” doc. IEEE 802.11-09/0334r8. It provides an update of the legacy indoor channel models for the conference room, enterprise cubicle and living room environments and defines new channel models for IEEE 802.11ay.

**Revision History**

r0 – Sept. 2015 – Initial version contains high level description of the proposed channel models to be used in IEEE 802.11ay group.

r1 – Nov. 2015 – Section 3 added, describing legacy channel models update to support SU-MIMO schemes.

r2 – Jan. 2016 – Section 4 and 5 added, introducing Quasi-Deterministic (Q-D) channel model development methodology and describing new channel models for large scale environments.

r3 – March 2016 – Section 4.5 added, describing the mobility effects within Q-D modeling approach. Section 6 added, with the description of the ultra-shout range channel model and measurements.

r4 – May 2016 – Section 7 added, describing D2D communications channel model, editorial changes were made.

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# Introduction

The TGay group started development of the new standard enhancing the efficiency and performance of existing IEEE 802.11ad specification providing Wireless Local Area Networks (WLANs) connectivity in 60 GHz band. The 11ay effort aims to significantly increase the data transmission rates defined in IEEE 802.11ad from 7 Gbps up to 30 Gbps on PHY layer which satisfies growing demand in network capacity for new coming applications, [1].

The scope of the new use cases considered in IEEE 802.11ay covers a very wide variety of indoor and outdoor applications including ultra-short range communications, high speed wireless docking connectivity, 8K UHD wireless transfer at smart home, augmented reality headsets and high-end wearables, data center inter-rack connectivity, mass-data distribution or video on demand system, mobile offloading and multi-band operation, mobile front-hauling, and wireless backhaul [2], [3].

Presented in [4] channel models for IEEE 802.11ad are focused on the indoor scenarios and SISO usage models. This document describes the new channel models applicable for evaluation of the IEEE 802.11ay systems performance. These channel models were developed based on the existing channel models for 60GHz WLAN systems [4], extensive ray-tracing simulations and the results of new experimental measurements provided by the MiWEBA FP7 ICT-2013-EU-Japan joint project consortium and other organizations participating in the development of the IEEE 802.11ay standard. The goal of the document is to support channel modeling and system performance evaluation for the use cases and scenarios considered in TG11ay and assist to IEEE 802.11ay standardization process.

Firstly, the document provides an extension of the legacy indoor Single Input Single Output (SISO) channel models for the conference room, living room, and enterprise cubicle environments, proposed in [4] and implemented in [5], for the case of Multiple Input Multiple Output (MIMO) systems. Secondly, the main results of new experimental measurements are discussed and the new Quasi-Deterministic (Q-D) methodology for channel modeling is introduced. Finally, the channel models for the basic new scenarios proposed in IEEE 802.11ay are described.

The rest of the document is organized as follows. Section II shortly reviews new channel models requirements for IEEE 802.11ay use cases, evaluation scenarios, and needed extensions for the existing IEEE 802.11ad channel models. Section III provides details of SU-MIMO extension methodology for all legacy indoor channel models. Section IV introduces the Quasi-Deterministic (Q-D) channel modeling methodology and provides an overview of available experimental results. Section V defines new IEEE 802.11ay channel models for large scale environments. Section VI defines Ultra Short Range (USR) channel model. Section VII provides the details of the D2D channel model development methodology and implementation details.

# Channel Model Requirements

## Basic Channel Model Requirements

IEEE 802.11ad channel model accurately describes the following channel modeling aspects:

* Space-time characteristics of the propagation channel (basic requirement) for main usage models of interest;
* Support beam forming with steerable directional antennas on both TX and RX sides with no limitation on the antenna technology;
* Account for polarization characteristics of antennas and signals;

IEEE 802.11ay include more complex scenarios, including dynamic outdoor environment support and support of various SU- and MU-MIMO modes. Thus, in addition to basic requirements, the 802.11ay channel model in the 60GHz band should:

* Support characteristics of the propagation channel in outdoor environment including non-stationary and mobility effects;
* Proper description of SU- and MU-MIMO modes;
* Ultra Short Range (USR) mmWave communication;

## IEEE 802.11ay Use Cases and Evaluation Scenarios

### IEEE 802.11ay Use Cases

IEEE 802.11ay proposes nine use cases to be used for performance evaluation of the future IEEE 802.11ay systems, [6]. The summary of the use cases proposed in [2] and supplementing docking station scenario proposed in [3] are provided in Table 2.1.

Table 2.1: Summary of proposed use cases in TGay.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **#** | **Applications and Characteristics** | **Propagation**  **Conditions** | **Throughput** | **Topology** |
| 1 | **Ultra Short Range (USR) Communications:**  -Static,D2D,  -Streaming/Downloading | LOS only, Indoor  <10cm | ~10Gbps | P2P |
| 2 | **8K UHD Wireless Transfer at Smart Home:**  -Uncompressed 8K UHD Streaming | Indoor, LOS with small NLOS chance, <5m | >28Gbps | P2P |
| 3 | **Augmented Reality and Virtual Reality:**  -Low Mobility, D2D  -3D UHD streaming | Indoor, LOS/NLOS  <10m | ~20Gbps | P2P |
| 4 | **Data Center NG60 Inter-Rack Connectivity:**  -Indoor Backhaul with multi-hop\* | Indoor, LOS only  <10m | ~20Gbps | P2P P2MP |
| 5 | **Video/Mass-Data Distribution/Video on Demand System:**  - Multicast Streaming/Downloading  - Dense Hotspots | Indoor, LOS/NLOS  <100m | >20Gbps | P2P P2MP |
| 6 | **Mobile Wi-Fi Offloading and Multi-Band Operation (low mobility):**  -Multi-band/-Multi-RAT Hotspot operation | Indoor/Outdoor, LOS/NLOS  <100m | >20Gbps | P2P P2MP |
| 7 | **Mobile Fronthauling** | Outdoor, LOS  <200m | ~20Gbps | P2P  P2MP |
| 8 | **Wireless Backhauling with Single Hop:**  -Small Cell Backhauling with single hop  -Small Cell Backhauling with multi-hop | Outdoor, LOS  <1km  <150m | ~2 – 20 Gbps | P2P  P2MP |
| 9 | **Office docking** | Indoor LOS/NLOS  < 3 m | ~13.2 Gbps | P2P  P2MP |

As it follows from Table 2.1 the considered use cases differ from each other by the throughput, latency, and topology configuration. Moreover the same use cases can be considered in different propagation environments (scenarios), and one environment scenario may host different usage models (and also different STA deployments, AP stations positions, interference environment, antenna configurations and other parameters).

Therefore for the channel modeling purposes, the classification of the channel models in accordance with scenarios and system operation mode is more appropriate.

### IEEE 802.11ay Evaluation Scenarios

Table 2.2 shows the correspondence between selected 802.11ay use cases [2] and channel modeling scenarios considered in present document.

Table 2.2 Use cases and channel modeling scenarios correspondence

|  |  |  |
| --- | --- | --- |
| **Channel modeling scenario** | **Use cases** | **Channel modeling approach  Supported mode of operation** |
| Living room | 2, 3 | 802.11ad model, extension for SU-MIMO |
| Enterprise cubicle | 5, 9 | 802.11ad model, extension for SU-MIMO |
| Conference room | 2,3,5 | 802.11ad model, extension for SU-MIMO |
| Open area Access/Fronthaul/Backhaul | 6,7,8,9 | 802.11ay models, MU-MIMO mode, low mobility |
| Street canyon | 6,7,8 | 802.11ay models, MU-MIMO mode, low mobility |
| Large indoor area:  Hotel lobby, Mall/Exhibition | 5, 6 | 802.11ay models, MU-MIMO mode, low mobility |
| Ultra-short range:  Kiosk Sync-and-go | 1 | Statistical approach based on measurements, SISO mode |
| Data center | 4 | New static LOS scenario: Metallic constructions, ceiling reflections. No experimental data.  MU-MIMO mode |
| Wearable D2D communications | 3 | Experimental measurements and ray-tracing simulations, SISO mode |

### Legacy IEEE 802.11ad Scenarios

The extensions of three legacy IEEE 802.11ad scenarios for SU-MIMO mode are considered in the document: Conference Room, Enterprise cubicle and Living room.

#### Conference Room

Small Conference Room (Figure 2‑1) scenario: in this scenario the link is established either between two STAs located on the table or between AP and STA with AP located near the ceiling in the conference room.



Figure 2‑1 Conference room scenario

#### Enterprise Cubicle

In the Enterprise Cubicle (EC) scenario shown in Figure 2‑2 the link is established between AP and STA with AP located near the ceiling above the chain of the cubicles and STA on the table inside the cubicle; cubicles are mounted at the large floor of the high tech building. The areas highlighted by yellow colour correspond to the areas where laptop can be placed. Cubicle 1 and 2 in Figure 2‑2 correspond to the “far zone” and cubicle 5 to the “near zone” based on their locations relative to the AP position.



Figure 2‑2 Enterprise cubicle scenario

#### Living Room

In the Living Room (LR) scenario shown in Figure 2‑3 the link is established between the set top box (STB) and TV receiving uncompressed video. The position of STB can be different in the room however the TV set is stationary mounted on one of the walls. The area highlighted in Figure 2‑3 corresponds to the possible laptop locations.



Figure 2‑3 Living room scenario

### New IEEE 802.11ay Channel Modeling Scenarios

In accordance with channel models classification represented in Table 2.2, four (TBD) new 802.11ay scenarios considered in this document.

#### Open area

Open area simulation scenario resembles the sparse environment with no closely spaced high buildings, such as park areas, university campuses, outdoor festivals, city squares or even rural areas (see Figure 2‑4).



Figure 2‑4: Open area (university campus)

The open area scenario is used as a baseline setup for millimeter-wave communication system evaluation, and simulated for the basic set of parameters and assumptions, summarized in Table 2.3.

Table 2.3. Open area scenario parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Cell Layout | Single cell, Hex grid (7 cells) |
| Number of sectors | 3 |
| ISD | 25-100 m (50m baseline) |
| AP height | 4m, 6m |
| STA height | 1.5m |
| Ground surface material | asphalt |
| Ground surface *εr* | 4 + 0.2j |
| Surface roughness σ | 3 mm |

#### Street canyon

The street canyon simulation scenario represents typical urban environment: streets with pedestrian sidewalks along the high-rise buildings. The access link between the APs on the lampposts and the STAs at human hands is modeled in this scenario (see Figure 2‑5).



Figure 2‑5: Street canyon access scenario

Deployment geometry the street canyon scenario is illustrated in Figure 2‑6 and Figure 2‑7.



Figure 2‑6: Street canyon scenario geometry



Figure 2‑7 AP sectors and positions in the Street canyon simulation scenario

The basic simulation parameters and assumptions are summarized in Table 2.4.

Table 2.4: Street canyon scenario parameters

|  |  |
| --- | --- |
| Parameter | Value |
| AP height, Htx | 6 m |
| STA height, Hrx | 1.5m |
| AP distance from nearest wall, Dtx | 4.5 m |
| Sidewalk width | 6 m |
| Road width | 16 m |
| Street length | 100 m |
| AP-AP distance, same side | 100 m |
| AP-AP distance, different sides | 50 m |
| Road and sidewalk material | Asphalt |
| Road and sidewalk εr | 4+0.2j |
| Ground roughness standard deviation σg | 0.2 mm |
| Building walls material | Concrete |
| Building walls εr | 6.25+0.3j |
| Building walls roughness standard deviation σw | 0.5 mm |

#### Hotel lobby

The hotel lobby simulation scenario covers many indoor access large public area use cases. Hotel lobby channel model represents typical indoor scenario: large hall with multiple users within (see Figure 2‑8).



Figure 2‑8: Hotel lobby scenario

The basic parameters and geometry of the hotel lobby simulation scenario are summarized in Table 2.5 and illustrated in Figure 2‑9.

Table 2.5: Hotel lobby (indoor access large public area) scenario parameters

|  |  |
| --- | --- |
| Parameter | Value |
| AP height, Htx | 5.5 m |
| AP position | Middle of the nearest wall (see Figure 2‑9) |
| STA height, Hrx | 1.5m |
| Room height | 6 m |
| Room width | 15 m |
| Room length | 20 m |
| Floor material | Concrete |
| Floor εrf | 4 + 0.2j |
| Floor roughness standard deviation σf | 0.1 mm |
| Walls material | Concrete |
| Walls εrw | 4 + 0.2j |
| Walls roughness standard deviation σw | 0.2 mm |
| Ceiling material | Plasterboard |
| Ceiling εrc | 6.25+0.3j |
| Ceiling roughness standard deviation σc | 0.2 mm |



Figure 2‑9: Hotel lobby (indoor access large public area) scenario

# MIMO Extension for IEEE 802.11ad Indoor Channel Models

This section provides an extension of the legacy IEEE 802.11ad channel model structure proposed in [4] for the case of Single User (SU) Multiple Input Multiple Output (MIMO) schemes using Phased Antenna Array (PAA) technology defined in [7]. Legacy IEEE 802.11ad channel models include Conference Room (CR), Enterprise Cubicle (EC), and Living Room (LR) environments in accordance with developed evaluation methodology in [6].

This section is organized as follows. Section 3.1 describes a channel structure for the Single Input Single Output (SISO) schemes using PAA with and without polarization support. Section 3.2 generalizes the channel structure considered in section 3.1 for the case of SU-MIMO schemes defined in [7]. Section 3.3 describes the practical steps to extend the IEEE 802.11ad channel model to support the proposed SU-MIMO configurations.

## General Channel Structure with Phased Antenna Arrays

The IEEE 802.11ad channel model defined in [4] proposes a channel structure that provides an accurate space-time characteristics and supports application of any type of directional antenna technology. It adopts the clustering approach with each cluster comprising of several rays closely spaced in time and spatial (angular) domains. This model allows for generating Channel Impulse Responses (CIRs) with and without polarization characteristics support. The present document follows the channel model development methodology proposed in [4] and extends the general channel structure description for the case of multi-element Phased Antenna Array (PAA) technology. First, general channel structure is introduced without polarization support and then it is modified to support polarization properties.

### General Channel Structure without Polarization Support

The channel in 60 GHz band can be represented as a superposition of the clusters or rays in space and time domain. Following the approach proposed in section 2.2 of the IEEE 802.11ad channel model document [4] the space-time point-to-point scalar CIR function in general case is defined as follows:

|  |  |
| --- | --- |
|  | (3.1) |

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*( )- 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 time of arrival, azimuth and elevation angles, gain of the cluster, and intra-cluster channel profile introduced in eq. (3.1) are generated using statistical Probability Density Functions (PDFs). The set of PDFs comprising the IEEE 802.11ad channel model was developed on the base of the experimental measurements and ray-tracing modeling. The IEEE 802.11ad channel model defines different distribution functions for different environments, however it keeps the same channel structure for all environments.

The eq. (3.1) defines channel structure in case of isotropic antennas for both transmitter and receiver sides and does not assume application of any beamforming algorithm. One of the basic requirements defined in the IEEE 802.11ad channel model supposes that any type of antenna can be applied. Assuming that one can introduce its own antenna technology and beamforming algorithm over the general channel model defined in eq. (3.1).

The theoretical equation describing CIR after application of beamforming is provided in section 6.1 of the document [4] and defined as follows:

|  |  |
| --- | --- |
|  | (3.2) |

where g*TX*(*φ, θ*) and g*RX*(*φ, θ*) are antenna gain functions (antenna patterns) for TX and RX antennas respectively. In 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 CIR includes all rays existing between TX and RX sides and can be exactly described by eq. (3.1) in that case.

In general 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 coordinates. But it should be noted that the CIR after application of beamforming at both TX and RX sides depends on the time variable only and does not depend on the angles of arrival and departure, i.e. spatial coordinates.

To introduce the general channel structure in case of PAA technology one can first consider a simplistic example of the CIR composing of only one ray and then generalize it for the case of multi-ray channel. Figure 3‑1 shows an illustration of the single ray channel between transmit and receive PAAs of linear 4 by 1 geometry.



Figure 3‑1: Illustration of single ray channel existing between transmit PAA #1 and receive PAA #2 phased antenna arrays defined as linear arrays of size 4 by 1.

The angles *θTX(i)* and *θRX(i)* define transmit and receive angular coordinates of the considered *i*-th channel ray. The angles are introduced in the system of coordinates associated with the PAA shown in Figure 3‑1.

In the far field zone the channel ray can be represented as a plane wave emitted by the PAA #1 and incident to the PAA #2. The incident plane wave described by the wave vector **k**, creates a linear phase shift for the array elements. A phase shift for the element with index nx (see Figure 3‑1) is defined as follows:

|  |  |
| --- | --- |
|  | (3.3) |

where *kx* defines the projection of wave vector on X axis, *dx* defines the spacing between array elements, *nx*defines the element index, *θRX(i)* defines an incident angle, and λ is a wavelength. It is assumed that the *dx* is a constant value and does not depend on the element index.

The *i*-ray channel phasor vector **Uich** of size *NRX* by 1 defines the linear phase shift between receive array’s elements and is written as follows:

|  |  |
| --- | --- |
|  | (3.4) |

Vector **Uich** is normalized to have unit power and avoid channel amplification. The vector component is defined in accordance with the following equation:

|  |  |
| --- | --- |
|  | (3.5) |

where *nx* denotes index of the array’s element.

Similar to the receive vector one can introduce the transmit *i*-ray channel phasor vector **Vich** as follows:

|  |  |
| --- | --- |
|  | (3.6) |

where *dx* defines the spacing between array elements, *θTX(i)* defines an emitting angle, and λ is a wavelength. It is also normalized to unit power. The vector component is defined as follows:

|  |  |
| --- | --- |
|  | (3.7) |

The eq. (3.4) and (3.6) for receive and transmit channel phasor vectors describing plane wave introduced for one dimensional linear array can be simply generalized for the case of two dimensional equidistant planar array of any size and any geometry.

Figure 3‑2 shows an example of planar array of size 4 by 4 and associated system of coordinates.



Figure 3‑2: Planar phased antenna array of size 4 by 4 and associated system of coordinates.

The phase shift for element with indexes (*nx*, *ny*) of two dimensional array for the receive direction (*θRX(i)*, *φRX(i)*) is defined as follows:

|  |  |
| --- | --- |
|  | (3.8) |

where *dx* and *dy* are the distances between elements along different array dimensions, *kx* and *ky* are projections of wave vector into the X and Y axis correspondingly, *θRX(i)* defines an incident elevation angle, *φRX(i)* defines an incident azimuth angle, and λ is a wavelength. In general case *dx* ≠ *dy*, however it is assumed that they are constant values defining equidistant elements location.

The two dimensional planar array supposes two dimensional indexing, however one can introduce one dimensional indexing in the following way:

|  |  |
| --- | --- |
|  | (3.9) |

where *Nx* is the number of elements along X axis, *Ny* is the number of elements along Y axis, and *Nx* \* *Ny* = *NRX*.

The receive channel phasor vector component is defined in accordance with the following equation:

|  |  |
| --- | --- |
|  | (3.10) |

Similar, the transmit channel phasor vector component is defined as follows:

|  |  |
| --- | --- |
|  | (3.11) |

Therefore even in the two dimensional case one can use one dimensional indexing and represent **Vich** and **Uich** channel phasor vectors using one dimensional column vector.

The channel space matrix describing the single ray channel between *NTX* and *NRX* elements for both one dimensional and two dimensional planar arrays can be written as follows:

|  |  |
| --- | --- |
|  | (3.12) |

where *A(i)* is an amplitude of the ray and **Uich** and **Vich** are channel phasor vectors defined by eq. (3.4) and (3.6) accordingly. Both vectors are column vectors and symbol H denotes Hermitian transpose function.

The channel matrix in eq. (3.12) defines the phase relations between all elements of two arrays. The amplitude does not depend on the element index and is equal to *A(i)* (far field assumption is true).

Note that matrix defined in eq. (3.12) has size of *NRX* by *NTX* and all its rows and columns are linear dependent. It follows that the single ray channel is described by the matrix with rank 1:

|  |  |
| --- | --- |
|  | (3.13) |

Generalizing the eq. (3.13) ffor the case of multi-ray channel one can represent it as a superposition of a number of rays. Assuming that each channel ray has its own time of arrival one can write the following equation:

|  |  |
| --- | --- |
|  | (3.14) |

where δ() is a delta function and *Nrays* defined the number of rays in the channel matrix. The eq. (3.14) defines a space-time channel structure and can have a rank greater than 1 for the time instance *t*. Two rays distinguishable in space domain and coming from different directions can be potentially indistinguishable in time domain, for example, in the environments with geometric symmetry. In another example the two rays can be potentially indistinguishable in time domain due to low enough sampling time resolution.

Note that for the simplicity of explanation the eq. (3.14) does not classify the rays comprising different clusters as it was introduced in the eq. (3.1). However this classification still can be applied if necessary.

The eq. (3.14) defines a general structure of the Multiple Input Multiple Output (MIMO) channel for PAA before beamforming application. It represents in the NRX by NTX matrix form and the matrix size depends on the total number of elements for the TX and RX PAAs. After application of beamforming at both transmitter and receiver sides the eq. (3.14) is reduced to the scalar case as follows:

|  |  |
| --- | --- |
|  | (3.15) |

where **V** and **U** are transmit and receive Antenna Weight Vectors (AWVs) accordingly. Vectors **V** and **U** are column vectors, hence **UHUich** and **(Vich)HV** define the dot products and the resulting CIR represents scalar variable depending on the time instant *t*.

Finally note that eq. (3.14) is a matrix counterpart of the scalar eq. (3.1) and eq. (3.15) is a counterpart of the eq. (3.2) introduced for the case of the Phased Antenna Array (PAA) technology.

### General Channel Structure with Polarization Support

The equations introduced in the previous section describe scalar and matrix Channel Impulse Responses (CIRs) without polarization support. However it was shown by the experimental study that the polarization has a significant impact on the 60 GHz signal propagation under both LOS and NLOS conditions, [10]. One of the basic requirements defined in the IEEE 802.11ad channel model supposes that polarization properties of the antennas and signals should be properly taken into account.

Therefore the IEEE 802.11ad channel model takes into account polarization properties and supports linear (vertical or horizontal), Left Hand Circular Polarization (LHCP), and Right Hand Circular Polarization (RHCP). The methodology introducing polarization support into the channel model is described in detail in section 2.4 in document [4]. The proposed methodology introduces Jones vector used in optics to describe the polarization property of the antenna and EM field.

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 3‑3.



Figure 3‑3. Transmitted E vector in the far field zone.

Vector **E** is perpendicular to the propagation direction defined by wave vector **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.

Jones vector **e** defines as a normalized two dimensional electrical field vector **E**. The first vector component is a real number, the second component is a complex number. The phase of the second component defines the phase difference between the orthogonal components of the **E** vector. The examples of the Jones vector for different polarization types defined in the IEEE 802.11ad model are summarized in Table 3.1.

Table 3.1: Examples of antennas polarization description using Jones vector.

|  |  |
| --- | --- |
| **Antenna polarization type** | **Corresponding Jones vector** |
| Linear polarized in the θ-direction | (1, 0) |
| Linear polarized in the φ-direction | (0, 1) |
| Left hand circular polarized (LHCP) | (1, j)/sqrt(2) |
| Right hand circular polarized (RHCP) | (1, -j)/sqrt(2) |

In the IEEE 802.11ad channel model polarization properties are introduced for the clusters and it is assumed that the rays comprising one cluster have identical polarization properties. In practice the difference on polarization for each intra-cluster ray still can be observed, however this difference is not so significant to introduce it into the model.

The Channel Impulse Response (CIR) introduced in the IEEE 802.11ad model extends the channel structure for polarization support and is described by the channel matrix **h** of size 2 x 2 as follows:

|  |  |
| --- | --- |
|  | (3.16) |

where **H(i)** defines a cluster polarization matrix. Note that the model for intra cluster channel impulse response *C*(*i*) is kept unchanged from the eq. (3.1), the only change in the general CIR structure is related to replacing cluster gain *A(i)* by the cluster polarization matrix **H(i)**. The matrix **H(i)** takes into account cluster gain and describes the attenuation of the cross-coupling links.

Assuming that the antenna polarization type is defined by Jones vector (see examples in Table 3.1), one can write the scalar CIR as follows:

|  |  |
| --- | --- |
|  | (3.17) |

where and are Jones vectors defining the polarization type for TX and RX antennas.

This document follows the same approach for polarization modeling introduced in [4]. The eq. (3.14) describing matrix CIR for Phased Antenna Array (PAA) can be modified to support polarization properties modeling as follows:

|  |  |
| --- | --- |
|  | (3.18) |

where **H(i)** is a 2 x 2 polarization matrix for ray with index i, and are Jones vectors defining the polarization type for TX and RX antennas. Components of polarization matrix **H(i)** define gain coefficients between the *Eθ* and *Eφ* components at the TX and RX antennas.

The scalar CIR after application of beamforming at both ends of the link with polarization support can be defined as follows:

|  |  |
| --- | --- |
|  | (3.19) |

where **V** and **U** are transmit and receive AWVs accordingly, and are Jones vectors defining the polarization type for transmit and receive antennas accordingly, and **H(i)** is a polarization matrix.

Therefore this section follows the channel model development methodology proposed in [4] and extends the general channel structure description for the case of Phased Antenna Array (PAA) technology with and without polarization support.

## Channel Structure for Considered SU-MIMO Configurations

This section generalizes the channel description for Phased Antenna Arrays (PAAs) introduced in the previous section to support more complex Single User (SU) Multiple Input Multiple Output (MIMO) configurations. The channel structure is considered by examples of SU-MIMO configurations proposed in [7]. The proposed SU-MIMO configurations exploit spatial and polarization diversity properties to create several spatial streams and allows system operation in LOS and NLOS conditions. The maximum SU-MIMO configuration is limited to 4 x 4 configuration and supports 4 streams.

### Channel Structure for SU-MIMO Configuration #1

The configuration #1 defines a symmetric link between two stations (STAs), each station has an identical PAA with single linear polarization (vertical or horizontal), and allows to set up a MIMO link with two spatial streams. Figure 3‑4 shows PAA configuration and examples of the beamformed links for the considered SU-MIMO configuration #1.

|  |  |
| --- | --- |
|  |  |
| **(a) SU-MIMO configuration** | **(b) Examples of beamformed links** |

Figure 3‑4: SU-MIMO configuration #1 – scheme and examples of beamformed links.

In this configuration each stream is assigned to its own phase shifter to create spatial separation. Note that one of the beamformed links for such scheme should be a NLOS link. Both streams cannot operate under LOS condition due to the poor separation in space domain.

The channel matrix for the 2 x 2 SU-MIMO scheme can be written using the notations introduced in section 3.1 for *i*-th ray as follows:

|  |  |
| --- | --- |
|  | (3.20) |

where **eV** is a Jones vector for vertical polarization (**eV** = (1, 0), see Table 3.1), (**V1**, **U1**) are TX/RX beamforming vectors for stream #1, (**V2**, **U2**) are TX/RX beamforming vectors for stream #2, **H(i)** polarization matrix for *i*-th ray, (**Vich**, **Uich**) are channel TX/RX phasor vectors defining phase relations between the elements of the TX/RX arrays.

The eq. (3.20) can be generalized for the case of multi-ray channel similar to that it was done for the PAA in the previous section as follows:

|  |  |
| --- | --- |
|  | (3.21) |

where **hMIMO i** is a MIMO matrix for *i*-th ray introduced in eq. (3.20), *t* is a time variable, and *ti* is a time instant corresponding to the time of arrival of *i*-th ray.

### Channel Structure for SU-MIMO Configuration #2

The configuration #2 defines a symmetric link between two stations (STAs), each station has an identical PAA with dual linear polarization (vertical and horizontal), and allows to set up a MIMO link with two spatial streams. Figure 3‑5 shows PAA configuration and examples of the beamformed links for the considered SU-MIMO configuration #2.

|  |  |
| --- | --- |
|  |  |
| **(a) SU-MIMO configuration** | **(b) Examples of beamformed links** |

Figure 3‑5: SU-MIMO configuration #2 – scheme and examples of beamformed links.

In this configuration each stream is assigned to its own phase shifter and its own polarization stream to extract both spatial and polarization separation. In that case both streams can operate under the LOS condition due to additional polarization separation in space domain. The experimental results provided in reference [9] shows that the practical PAA design can provide -23.0 – -24.0 dB cross polarization discrimination (XPD) factor. This scheme allows flexible beamformed link adaptation as shown in Figure 3‑5 (b).

The channel matrix for the 2 x 2 SU-MIMO scheme for *i*-th ray can be written using the notations introduced in section 3.1 as follows:

|  |  |
| --- | --- |
|  | (3.22) |

where **eV** is a Jones vector for vertical polarization (**eV** = (1, 0), see Table 3.1), **eH** is a Jones vector for horizontal polarization (**eH** = (0, 1), see Table 3.1), (**V1**, **U1**) are TX/RX beamforming vectors for stream #1, (**V2**, **U2**) are TX/RX beamforming vectors for stream #2, **H(i)** polarization matrix, (**Vich**, **Uich**) are channel TX/RX phasor vectors defining phase relations between the elements of the arrays. A general structure for the multi-ray channel can be written as in eq. (3.21).

### Channel Structure for SU-MIMO Configuration #3

The configuration #3 defines a symmetric link between two STAs, each STA has two PAAs with single linear polarization (vertical or horizontal), and allows to set up a MIMO link with two spatial streams. Figure 3‑6 shows PAAs configuration and examples of the beamformed links for the considered SU-MIMO configuration #3.

|  |  |
| --- | --- |
|  |  |
| **(a) SU-MIMO configuration** | **(b) Examples of beamformed links** |

Figure 3‑6: SU-MIMO configuration #3 – scheme and examples of beamformed links.

In this configuration each stream is assigned to its own PAA. The PAAs at the transmitter and receiver sides are separated by the distances d1 and d2, respectively. In that case both streams can operate under the LOS condition up to several meters due to PAAs separation in space. The maximum distance which guarantees reliable reception under the LOS condition depends on the PAA particular design and separation distances d1 and d2. The experimental results provided in reference [9] shows that the PAA separation by 30 cm (typical laptop edge size) with PAAs of 2 x 8 geometry guarantees cross-links attenuation by -15 dB comparing to the power of direct links up to the distance of 2 m between transmitter and receiver.

The channel matrix for the 2 x 2 SU-MIMO scheme for *i*-th ray can be written using the notations introduced in Section 3.1 as follows:

|  |  |
| --- | --- |
|  | (3.23) |

whereis a Jones vector for vertical polarization ( = (1, 0), see Table 3.1), is a Jones vector for horizontal polarization ( = (0, 1), see Table 3.1), (**V1**, **U1**) are TX/RX beamforming vectors for stream #1, (**V2**, **U2**) are TX/RX beamforming vectors for stream #2, **H(i)** polarization matrix, (**Vijkch** **Uijkch**) are channel TX/RX phasor vectors defining phase relations for the i-th ray between k-th transmit PAA and j-th receive PAA, respectively. Note that the eq. (3.23) assumes that PAAs have different polarization types to further improve the cross-link attenuation. A general structure for the multi-ray channel can be written as in eq. (3.21).

### Channel Structure for SU-MIMO Configuration #4

The configuration #4 defines a symmetric link between two STAs, each STA has two PAAs with dual linear polarization (vertical and horizontal), and allows to set up a MIMO link with 4 spatial streams. Figure 3‑7 shows PAAs configuration and examples of the beamformed links for the considered SU-MIMO configuration #4.

|  |  |
| --- | --- |
|  |  |
| **(a) SU-MIMO configuration** | **(b) Examples of beamformed links** |

Figure 3‑7: SU-MIMO configuration #4 – scheme and examples of beamformed links.

In this configuration each stream is assigned to its own PAA and its own phase shifter and polarization inside each PAA. Basically this configuration combines the properties of configuration #2 and #3 considered above. This scheme allows flexible beamformed link adaptation as shown in Figure 3‑7 (b).

The channel matrix for the 4 x 4 SU-MIMO scheme for *i*-th ray can be written using the notations introduced in section 3.1 as follows:

|  |  |
| --- | --- |
|  | (3.24) |

where  is a Jones vector for vertical polarization ( = (1, 0), see Table 3.1), is a Jones vector for horizontal polarization ( = (0, 1), see Table 3.1), (**V1**, **U1**) are TX/RX beamforming vectors for stream #1, (**V2**, **U2**) are TX/RX beamforming vectors for stream #2, **H(i)** polarization matrix, (**Vijkch**, **Uijkch**) are channel TX/RX phasor vectors defining phase relations for the i-th ray between k-th transmit PAA and j-th receive PAA, respectively. A general structure for the multi-ray channel can be written as in eq. (3.21).

### Channel Structure for SU-MIMO Configuration #5

The configuration #5 defines an asymmetric link between two STAs, the first STA has single PAA with linear polarization (vertical or horizontal), and the second STA has single PAA with dual polarization (vertical and horizontal). It allows to set up a SIMO link with 1 spatial stream. Figure 3‑8 shows PAAs configuration and examples of the beamformed links for the considered SU-MIMO configuration #5.

|  |  |
| --- | --- |
|  |  |
| **(a) SU-MIMO configuration** | **(b) Examples of beamformed links** |

Figure 3‑8: SU-MIMO configuration #5 – scheme and examples of beamformed links.

This configuration allows robust Maximum Ratio Combining (MRC) reception of the single stream.

The channel matrix for the 1 x 2 SIMO scheme for *i*-th ray can be written using the notations introduced in section 3.1 as follows:

|  |  |
| --- | --- |
|  | (3.25) |

where **eV** is a Jones vector for vertical polarization (**eV** = (1, 0), see Table 3.1), **eH** is a Jones vector for horizontal polarization (**eH** = (0, 1), see Table 3.1), (**V1**, **U1**) are TX/RX beamforming vectors for stream #1, (**V1**, **U2**) are TX/RX beamforming vectors for stream #2, **H(i)** polarization matrix, (**Vich**, **Uich**) are channel TX/RX phasor vectors defining phase relations between the elements of the arrays. A general structure for the multi-ray channel can be written as in eq. (3.21).

### Summary of Proposed SU-MIMO Configurations

The summary of the proposed SU-MIMO configurations is provided in Table 3.2. In general case PAA has rectangular geometry of M x N and distance between arrays d1, d2. M, N, and d1, d2 are parameters and can be changed for the sake of channel modelling.

Table 3.2: Summary of considered SU-MIMO configurations.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **#** | **Number of data streams** | **MIMO**  **Configuration** | **Number of PAAs**  **(Device 1, Device 2)** | **Polarization type**  **(Device 1, Device 2)** | **PAAs separation (Device 1, Device 2)** | **Number of RF parts per PAA**  **(Device 1, Device 2)** | **Mandatory /**  **Optional[[1]](#footnote-1)** |
| **1** | 2 | 2 x 2 | (1, 1) | (Single, single) | (0, 0) | (2, 2) | Optional |
| **2** | 2 | 2 x 2 | (1, 1) | (Dual, dual) | (0, 0) | (2, 2) | Mandatory |
| **3** | 2 | 2 x 2 | (2, 2) | (Single, single) | (d1, d2) | (1, 1) | Mandatory |
| **4** | 4 | 4 x 4 | (2, 2) | (Dual, dual) | (d1, d2) | (2, 2) | Optional |
| **5** | 1 | 1 x 2 | (1, 2) | (Single, dual) | (0, 0) | (1, 2) | Mandatory |

The considered SU-MIMO configurations are implemented on the base of the existing IEEE 802.11ad channel model Matlab software described in [5].

## IEEE 802.11ad Channel Model Extension to Support SU-MIMO Configurations

The proposed SU-MIMO configurations can be supported in the Matlab software implemented the IEEE 802.11ad channel model and provided in [5]. The upgrade of the existing channel model software includes the following steps:

1. **Support of Phased Antenna Array (PAA)** – this is a straightforward step, since in accordance with the basic requirements the IEEE 802.11ad model can support any antenna technology;
2. **Support of SU-MIMO schemes** – SU-MIMO schemes summarized in the Table 3.2 should be supported, however one can introduce the proprietary MIMO schemes on the base of the extended software infrastructure;
3. **Support of beamforming algorithm for SU-MIMO** – default algorithm should be defined to set up the transmit and receive Antenna Weight Vectors (AWVs) **V** and **U**, however one can introduce a proprietary beamforming defining **V** and **U** in a different way;

The following subsections describe the proposed IEEE 802.11ad channel model modifications in detail.

### Support of Phased Antenna Array Technology

The support of the Phased Antenna Array (PAA) technology is straightforward and can be done as follows. The spatial coordinates for all channel rays are defined in the basic system of coordinates associated with transmitter and receiver defined in Section 6.3.3 in [4] and shown in Figure 3‑9.



Figure 3‑9: Basic system of coordinates associated with the transmitter and receiver in the beam search procedure.

The existing Matlab software implemented the IEEE 802.11ad channel model for each scenario provides the spatial coordinates of the rays introduced in the system of coordinates shown in Figure 3‑9. To set up a location of the PAA in the basic system of coordinates one can set up a location of system of coordinates associated with PAA and shown in Figure 3‑2 relative to the basic system of coordinates shown in Figure 3‑9. The precise location can be defined applying Euler’s rotations described in detail in Section 6.3.3 in [4].

Then the spatial coordinates of the rays can be recalculated from the basic system of coordinates to the one associated with the PAA. Assuming that the azimuth and elevation angles for each ray is known one can apply eq. (3.14) to define the space-time channel structure. After that one can apply any beamforming procedure to define transmit and receive (**V** and **U)** Antenna Weight Vectors (AWVs) to obtain the beamformed channel defined in eq. (3.15).

### Support of SU-MIMO Schemes

The SU-MIMO schemes summarized in the Table 3.2 use the PAA with single or dual polarization and up to 2 PAAs at each TX/RX side of the communication link. The IEEE 802.11ad channel model supports polarization modelling introducing the polarization matrix **H(i)** for the channel cluster or ray. The dual polarizations required for SU-MIMO modelling can be supported calculating the channel for all linear polarization combinations as follows:

1. TX vertical (V) -> RX vertical (V);
2. TX vertical (V) -> RX horizontal (H);
3. TX horizontal (H) -> RX vertical (V);
4. TX horizontal (H) -> RX horizontal (H);

This can be done by calculating the corresponding cluster gain coefficients as follows:

|  |  |
| --- | --- |
|  | (3.26) |

The MIMO schemes utilizing two PAAs at the transmitter or receiver side can be also simply supported associating two PAAs with one system of coordinates which can be located relative to the basic system of coordinates shown in Figure 3‑9.

Figure 3‑10 shows the system of coordinates associated with two PAAs required for SU-MIMO modelling.



Figure 3‑10: System of coordinates associated with two PAAs required for SU-MIMO modelling.

The origin for the system of coordinates is collocated with the geometrical centre of the PAA #1. The PAA #2 is located by the distance d from the origin which is defined as a parameter. The recalculation of the ray angular coordinates is done similar to that discussed in the previous section.

The SU-MIMO configuration with dual arrays requires introduction of spatial correlation between PAAs spaced by the distance d. Note that the legacy IEEE 802.11ad channel model provides inter cluster model for the SISO case only. The statistical distributions describing spatial (angular) and time coordinates of the clusters were obtained on the base of the ray-tracing approach described in detail in Section 3.2 in [4].

To support SU-MIMO configurations the inter-cluster model is replaced by the ray-tracing algorithm predicting cluster spatial (angular) and time coordinates for the given transmitter and receiver locations and environment geometry defined in [4], but in contrast to the SISO case it provides coordinates between 4 points in space corresponding to the coordinates of TX and RX PAAs. Figure 3‑11 shows an example of the clusters distribution for the Conference Room (CR) station to station (STA-STA) sub-scenario described in Section 3 in [4]. The red and blue circles define transmit and receive antennas accordingly spaced by the distance of 30 cm. Note that Figure 3‑11 shows first order reflections only.

|  |  |
| --- | --- |
|  |  |
| **(a) Inter-cluster structure in 3D space** | **(b) Inter-cluster structure in 2D XY plane projection** |

Figure 3‑11: Example of inter-cluster structure plotted using ray-tracing algorithm for the SU-MIMO in conference room scenario.

So, the SU-MIMO configurations use ray-tracing algorithm to predict spatial and time coordinates for the clusters instead of the inter-cluster model. However, it uses the same intra-cluster model based on the results of the experimental measurements and described in Section 3.7 in [4].

### Support of Beamforming Algorithm

The considered SU-MIMO configurations can support any type of the beamforming by applying suitable transmit and receive (**V** and **U)** AWVs. The companies participating in the IEEE 802.11ad standard development can use proprietary beamforming algorithms specifying vectors **V** and **U**. However for the sake of the channel modeling it is proposed to consider simple default Maximum Power Ray (MPR) beamforming algorithm introduced in Section 6.5 in [4]. It steers the maximum antenna gain to the spatial coordinates corresponding to the ray with the maximum power.

In case of the MPR algorithm the transmit AWV **V** can be simply defined as follows:

|  |  |
| --- | --- |
|  | (3.27) |

It assumes linear phase shift for the elements of the array. It steers the maximum antenna gain to the spatial direction with the angular coordinates (φTX, θTX).

In similar way one can introduce receive AWV **U** as follows:

|  |  |
| --- | --- |
|  | (3.28) |

where (φRX, θRX) defines angular coordinates for reception.

In the MPR algorithm (φTX, θTX) and (φRX, θRX) are selected equal to the spatial coordinates of the ray with the maximum power.

In case of the SU-MIMO configuration #1 considered in Section 3.2.1 and representing single array with single polarization the MPR algorithm can be generalized to select 2 rays with the maximum power in order to create two spatial streams.

### Usage of Channel Model in Simulations

This section gives a brief overview of the channel impulse response generation process implemented in the Matlab software providing IEEE802.11ad channel model extension to the SU-MIMO case. The process is schematically shown in Figure 3‑12 and similar to that described in Section 2.5 in [4] for the SISO case.



Figure 3‑12: Process of channel realization generation.

The first difference from the legacy process is that the block generating inter cluster parameters includes the block implementing ray-tracing algorithm highlighted by the red square in Figure 3‑12. It predicts the angular and time domain cluster coordinates based on the geometrical optics law instead of the inter-cluster statistical model developed in the IEEE 802.11ad channel model and described in [4]. This allows to introduce easier space correlation between the antennas as it is shown in Figure 3‑11 for the SU-MIMO case.

The second difference from the legacy process is that the block implementing antenna models includes Phased Antenna Array (PAA) model. One can select the geometry and the number of elements in the PAA, polarization types for both antennas (if dual array configuration is considered) for both transmitter and receiver, and polarization types for the PAAs for both transmitter and receiver. New block is highlighted by the red square in Figure 3‑12.

At the output the channel model software provides the number of channel impulse responses in time domain sampled at the given sample rate. For example, for 2x2 SU-MIMO system it provides 4 channel impulse responses for the direct links h11(n), h22(n) and cross links h12(n), h21(n) where n defines a time sample index. For the maximal SU-MIMO configuration #4 it provides 16 channel impulse responses accordingly.

The sampling rate parameter can be selected equal to any value, therefore if one needs to model channel bonding of several channels one can select it equal to 2.64 GHz, 2 x 2.64 GHz, 3 x 2.64 GHz, or 4 x 2.64 GHz.

# Quasi-Deterministic Approach for New IEEE 802.11ay Scenarios

## New Experimental Measurements and Rays Classification

New experimental measurement results obtained for different outdoor environments in MiWEBA project [21][22][23][24][26][27] show that millimeter-wave channel for complex large area outdoor environments may not be completely described by the deterministic ray-tracing approach. The more detail analysis of the experimental results leads to the conclusion that realistic millimeter-wave channel models can consist of deterministic components, defined by the scenario and random components, representing unpredictable factors or random objects appeared in this environment.

Such approach, called quasi-deterministic (Q-D), was offered for modeling access and backhaul millimeter-wave channels at 60 GHz [18][24]. The approach builds on the representation of the millimeter-wave channel impulse response comprised of a few quasi-deterministic strong rays (D-rays), a number of relatively weak random rays (R-rays, originating from the static surfaces reflections) and flashing rays (F-rays, originating by reflections from moving cars, buses and other dynamic objects), see Figure 4‑1.

The first type of rays (D-rays) makes the major contribution into the signal power, presents all the time and usually can be clearly identified as reflection from scenario-important macro objects. It is logical to include them into the channel model as deterministic (D-rays), explicitly calculated values. The element of randomness, important for the statistical channel modeling may be introduced on the intra-cluster level, by adding random exponentially decaying cluster to the main D-ray.

The second type of rays (R-rays) is the reflections from the random objects or the objects that is not mandatory in the scenario environment. Such type of rays may be included in the model in a classical statistical way, as rays with parameters (AoD, AoA, PDP) selected randomly in accordance with the pre-defined distributions.

The third type of rays, (F-rays) may be introduced in the channel model for the special non-stationary environments. These rays can appear for the short period of time, for example, as a reflection from the moving cars and other objects. The F-rays can be described in the same way as the R-rays, but taking into account the statistics of their appearance in time.



Figure 4‑1 D-, R- and F-rays in the Q-D model illustration

All types of rays are then combined in the single clustered channel impulse response, schematically shown in Figure 4‑2. Here cluster refers to multi path components with similar delay, AoD, and AoA parameters. All of these parameters should be similar for all these multi path components. Physically it means that the paths belonging to the same cluster should have the same physical propagation mechanisms (e.g. produced by one physical reflection surface) [15].

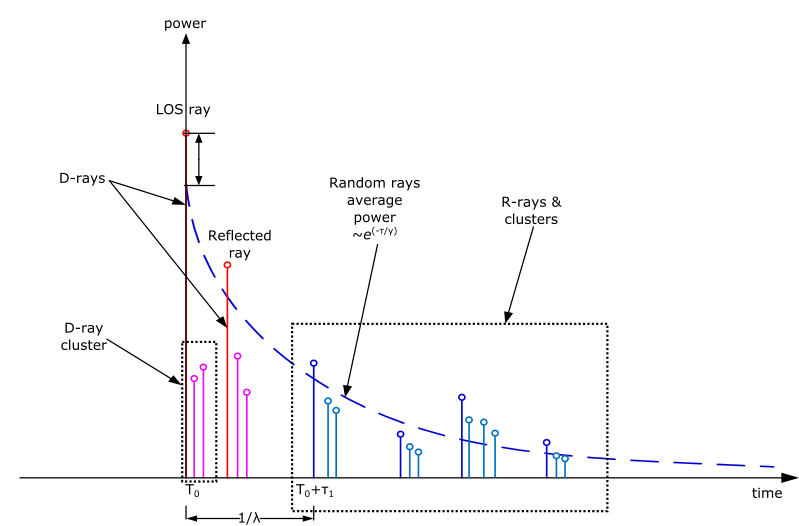


Figure 4‑2: Q-D channel model channel impulse response structure

For each of the channel propagation scenarios, the strongest propagation paths are determined and associated to rays which produce the substantial part of the received useful signal power. Then the signal propagation over these paths is calculated based on the geometry of the deployment and the locations of transmitter and receiver, calculating the ray parameters, such as angles of arrival and departure, power and polarization characteristics. The signal power conveyed over each of the rays is calculated in accordance to theoretical formulas taking into account free space losses, reflections, antennas polarization and receiver mobility effects like Doppler shift. Some of the parameters in these calculations may be considered as random values like reflection coefficients or as random processes like receiver motion. The number of D-rays, which are taken into account, is scenario dependent and is chosen to be in line to the channel measurement results. Additionally to the D-rays, a number of other reflected waves are received from different directions, coming for example from cars, trees, lamp posts, benches, houses, etc. (for outdoor scenarios) or from room furniture and other objects (for indoor scenarios). These rays are modeled as R-rays. These rays are defined as random clusters with specified statistical parameters extracted from available experimental data or ray tracing modeling.

For a given environmental scenario, the process of the definition of a D-rays, R-rays, F-rays and their parameters is based both on the experimental measurements and ray-tracing reconstruction of the environment. The experimental measurements processing includes peak detection algorithm with further accumulation of the peak statistics over time, identifying the percentage of the selected ray activity during observation period. For example, based on the analysis of available experimental data [24], the rays with activity percentage above 80-90% may be classified as the D-rays: strong and always present, if not blocked. The blockage percentage for D-rays may be estimated around 2-4%. The rays with activity percentage about 40-70% are the R-rays: the reflections from far-away static objects, weaker and more susceptible to blockage due to longer travel distance. And finally, the rays with activity percentage below 30% are the F-rays: the flashing reflection from random moving objects. Such rays are not “blocked”, they actually “appear” only for a short time.

Figure 4‑3 illustrates the channel impulse response generation process as a pipeline, similar to Figure 3‑12.



Figure 4‑3 Process of channel impulse response generation for Q-D approach

The core of the algorithm consist of the three major steps D-rays generation (Section 4.2), R-rays generation (Section 4.3) and adding the thin intra-cluster structure to the generated D- and R-rays (Section 4.3). These three steps are illustrated in Figure 4‑4.



Figure 4‑4 Base steps of channel impulse response generation

## D-Rays Modeling

The quasi-deterministic rays are explicitly calculated in accordance with scenario parameters, geometry and propagation conditions. The propagation loss is calculated by Friis equation, with taking into account additional losses from the oxygen absorption (Table 4.1, second row). Important part of the proposed Q-D approach to the channel modelling is the calculation of the reflected ray parameters. The calculations are based on the Fresnel equations, with additionally taken into account losses due to surface roughness (Table 4.2, second row)

The feasibility of the proposed approach to the prediction of the signal power is proven in [28] for outdoor microcell environments and in [29] and [30] for inter-vehicle communication modelling. In general, problems of the signal power prediction are considered in [31].

The D-rays are strictly scenario-dependent, but in all considered outdoor scenarios two basic D-rays are present: the direct LOS ray and the ground reflected ray. The calculation of those two basic rays parameters will be the same for all scenarios.

### Direct Ray

Direct LOS ray is a ray between TX and RX.

Table 4.1 Direct ray parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Delay | Direct ray delay is calculated from the model geometry: |
| Power | Direct ray power calculated as free-space pathloss with oxygen absorption:  , in dB |
| Channel matrix |  |
| AoD | 0˚ azimuth and elevation |
| AoA | 0˚ azimuth and elevation |

### Ground Reflected Ray

Ground-reflected ray presents in all considered scenarios. Its parameters calculated based on Friis free space pathloss equation and the Fresnel equation to take into account reflection and rough surface scattering factor F. Note that the horizontally and vertically polarized components of the transmitted signal will be differently reflected and thus, the channel matrix should have different diagonal elements.

Table 4.2 Ground-reflected ray parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Delay | Ground-reflected ray delay is calculated from the model geometry: |
| Power | Ground-reflected power calculated as free-space pathloss with oxygen absorption, with additional reflection loss calculated on the base of Fresnel equations. Reflection loss R is different for vertical and horizontal polarizations  for horizontal polarization.  for vertical polarization,  where and is a surface roughness |
| Channel matrix |  |
| AoD | Azimuth: 0˚, Elevation: |
| AoA | Azimuth: 0˚, Elevation: |

### Additional D-Rays

For the open-area scenario, with no significant reflection objects other than ground, only two D-rays considered. However, in more rich scenarios, like considered here large square, or for example, street canyon scenario, refection from one or more walls should be taken into account. The principle of calculation of these additional D-rays is the same, detailed description may be found in [24]. The closest wall can be calculated using the geometry and positions of the transmitter and receiver. The calculation of the path properties is similar to the ground ray reflection considered in the previous section taking into account material properties for the specific environments.

## R-rays Modeling

In order to take into account a number of rays that cannot be explicitly described deterministically (reflections from objects that are not fully specified in the scenario, objects with random or unknown placement, objects with complex geometry, higher-order reflections, etc.) the R-rays are introduced in the Q-D modeling methodology. The R-rays may be generated in two different ways: statistically in accordance with the pre-defined power-delay profile or as deterministic reflections from random objects.

### Statistical R-Rays Definitions

Statistical approach is a basic way of R-rays generation is used in the Q-D channel modeling methodology. The clusters (see Figure 4‑2) arrive at moments *τk* according to Poisson process and have inter-arrival times that are exponentially distributed. The cluster amplitudes *A*(*τk*) are independent Rayleigh random variables and the corresponding phase angles *θk* are independent uniform random variables over [*0,2π*]

The random rays components of the channel impulse response are given by:

(4.1)

where *τk* is the arrival time of the *k*-th cluster measured from the arrival time of the LOS ray, *A*(*τk*), *P*(*τk*)and *θk* are the amplitude, power and phase of the *k*-th cluster. The R-rays are random, with Rayleigh-distributed amplitudes and random phases, with exponentially decaying power delay profile. The total power is determined by the K-factor with respect to the direct LOS path.

(4.2)

(4.3)

Table 4.3 summarizes the R-rays parameters for the open area/large square models. The power-delay profile parameters are derived based on the available experimental data and corresponding ray-tracing simulations. The AoA and AoD ranges illustrate the fact that random reflectors can be found anywhere around the receiver, but are limited in height. Uniform distributions are selected for simplicity and can be further enhanced on the base of more extensive measurements.

Table 4.3 Open square model R-Rays parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Number of rays, *N* | 3 |
| Poisson arrival rate, λ | 0.05ns-1 |
| Power-decay constant, γ | 15ns |
| *K*-factor | 6dB |
| AOA | Elevation: U[-20:20˚]  Azimuth: U[-180:180˚] |
| AOD | Elevation: U[-20:20˚]  Azimuth: U[-180:180˚] |

In the 802.11ad channel model [4], the set of approximations were proposed for diagonal and off-diagonal elements of the channel matrix **H** for the first- and second-order reflections in typical indoor environments (conference room, cubicle, and living room) as combination of log-normal and uniform distributions on the base of experimental studies [32]. In the Q-D model the ray amplitude approximated by the Rayleigh distribution (which is close to log-normal) so to the simple fixed polarization matrix **H**p may be used for introducing polarization properties to the R-rays (matrix **H** is obtained by multiplication the scalar amplitudes *A* to the polarization matrix **H**p). The polarization matrix **H**p for R-rays is defined by:

(4.4)

The values with sign ± assumed to have random sign, (+1 or -1, for instance) with equal probability, independently from other values. The polarization matrix is identical for all rays comprising the cluster.

Flashing rays, or F-rays introduced are intended to describe the reflections from fast moving objects like vehicles and are short in duration. Its properties require an additional investigations and analysis, thus the F-rays are not included in the considered Q-D modeling approach application example.

### Random Objects Reflections R-Rays

The synthetic aperture processing of the experimental results [25] have shown that the reflections from various environmental objects such as trees, lampposts, bus stops etc. can be clearly identified (with exact estimation of the reflector position) from the experimental data. Such rays should be taken into account along with D-rays, which originates from large-scale objects, but the definition of the position of each reflector makes scenario description complex and very specific. Thus, it is proposed to generate such type of rays (R-rays or F-rays) as reflections from the randomly placed spherical objects, that (unlike the flat objects) can create specular reflection path between any two points in the 3D space.

For now, based on the experimental measurements, the R-rays as reflections from random objects are introduced for Street Canyon scenario only, in addition to statistically generated R-rays described above. Also, the F-rays generates in this way, with only difference of the path existence period in the applications where the longer periods of time are analysed.

The parameters of R- and F-rays generated as random reflections defined in the Street Canyon channel model section (Section 5.2).

## Intra-Cluster Structure Modeling

The surface roughness and presence of the various irregular objects on the considered reflecting surfaces and inside them (bricks, windows, borders, manholes, advertisement boards on the walls, etc.) lead to separation the specular reflection ray to a number of the additional rays with close delays and angles: a cluster. The intra cluster parameters of the channel model were extracted from the indoor models [4], obtained from the measurement data presented in [8]. The intra-cluster structure is introduced in the Q-D model in the same way as R-rays: as Poisson-distributed in time, exponentially decaying Rayleigh components, dependent on the main ray.

The identification of rays inside of the cluster in the angular domain requires very high angular resolution. The “virtual antenna array” technique, where low directional antenna element is used to perform measurements in multiple positions along the virtual antenna array to form an effective antenna aperture, was used in the MEDIAN project [33] [34]. These results were processed in [35], deriving the recommendation to model the intra-cluster angle spread for azimuth and elevation angles for both transmitter and receiver as independent normally distributed random variables with zero mean and RMS equal to 50: N(0, 50).

Note that it is reasonable to assume that different types of clusters may have distinctive intra cluster structure. For example, properties of the clusters reflected from the road surface are different from the properties of the clusters reflected from brick walls because of the different materials of the surface structure. Also one may assume the properties of the first and second order reflected clusters to be different, with the second order reflected clusters having larger spreads in temporal and angular domains. All these effects are understood to be reasonable. However since the number of available experimental results was limited, a common intra cluster model for all types of clusters was developed. Modifications with different intra cluster models for different types of clusters may be a subject of the future channel model enhancements.

In the 802.11ay channel model the intra cluster structure is added to the D-rays and R-rays base structure (Figure 4‑4, step 3).

For every base ray, the intra cluster structure is given by:

(4.5)

where *τk* is the arrival time of the *k*-th intra-cluster component measured from the arrival time of the base D-ray or R- ray, *A*(*τk*), *P*(*τk*)and *θk* are the amplitude, power and phase of the *k*-th intra-cluster component. The intra-cluster components are random, with Rayleigh-distributed amplitudes and random phases, with exponentially decaying power delay profile. The total power is determined by the K-factor with respect to the base D- ray or R-ray power:

(4.6)

(4.7)

Generally, the intra-cluster structure generation is very similar to the R-rays generation, except that for R-rays generation the LOS rays is used as a timing and power base, and for intra-cluster structure generation cluster-base D-ray or R-ray is used for that purpose.

Combining all D-rays, R-rays and their respective intra-cluster structure components will give the final channel impulse response in the form of Eq. 3.1.

## Mobility Effects

The mobility effects in the Q-D channel model are described by direct introducing the velocity vector for each STA. In multi-path channel the STA movement leads to additional phase rotation for each propagation path. For the purposes of the channel modeling, the motion effect can be introduced for D-rays and R-rays in the same way.

The additional phase rotation for *i*-th ray caused by Doppler frequency shift is calculated as:

(4.8)

(4.9)

where is the frequency shift for *i*-th ray, ***v*** is the instantaneous vector of STA velocity (see Figure 4‑5 Model for mobility effects in 3D channel model), ***r****i* is the unity vector of the *i*-th ray direction of arrival, *Fc* is carrier frequency and (,) denotes scalar product.



Figure 4‑5 Model for mobility effects in 3D channel model

The velocity vector ***v*** can be represented as sum of its scalar components:

(4.10)

The horizontal components of the velocity vector are scenario specific. For scenarios without preferred direction of motion, such as open area, the horizontal component of velocity may have uniformly distributed direction and random or fixed value. For example, they may by described by two-dimensional zero mean Gaussian PDF with appropriate standard deviations σx, σy:

, . (4.11)

As it was shown in experimental measurements [44] the vertical movement of the pedestrian mobile STA has significant impact on the channel and also should be taken into account. In the important case when the mobile STA is held by a human, the different models of human gait can be applied for vertical motion *z*(*t*) description. In accordance with the Q-D methodology, the vertical motion is introduced as a stationary Gaussian random process. For the considered case of human gait the following correlation function of *z(t)* can be applied:

(4.12)

with parameters, adjusted to the real pedestrian motion with the speed 3-5 km/h. The vertical component *vz* of the velocity vector ***v*** can be defined through the user vertical motion as the first derivative.

With the knowledge of the velocity vector and rays angles of arrival, the values of the phase rotations can be calculated from Eq. 4.8 and added to the corresponding D-rays and R-rays phases.

## Channel Impulse Response Post Processing

Channel impulse response post processing may include application of the antenna pattern, beam steering algorithms and sampling the CIR to the desired discrete rate (see Figure 4‑3). These steps are the same for 802.11ad and 802.11ay models. The MIMO processing for the case of two or more phased antenna arrays discussed in Section 3 of present document, generalized approach for antenna pattern application and channel impulse response sampling presented in [4].

# New IEEE 802.11ay Channel Models for Large Scale Environments

## Open Area Outdoor Hotspot Access

### D-Rays Parameters

The set of D-rays for open area scenario includes only two rays: direct LOS and ground reflected ray (See Figure 5‑1). Both rays are described in Section 4.2. The exact values of the antenna heights, positions and properties of ground surface are specified in the detailed scenario description (Section 2.2.4).



Figure 5‑1: Open area scenario

### R-Rays Parameters

In addition to main deterministic components the direct and ground rays, there are random components that represent reflection scattering. The reflection from the distant walls, random objects and second-order reflection are taken into account as random components, their parameters are summarized in Table 5.1.

Table 5.1: Open area model R-rays parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Number of rays, *N* | 3 |
| Poisson arrival rate, λ | 0.05ns-1 |
| Power-decay constant, γ | 15ns |
| *K*-factor | 6dB |
| AOA | Elevation: U[-20:20˚]  Azimuth: U[-180:180˚] |
| AOD | Elevation: U[-20:20˚]  Azimuth: U[-180:180˚] |

### Intra-Cluster Parameters

Both D-rays and R-rays in the open-area channel model have thin cluster structure that adds post-cursor rays to the main D-ray and R-ray component. Although the direct LOS ray may also have clustered structure due to propagation path variations and partially closed by obstacles Fresnel zones, in the proposed model direct ray do not have clustering. The parameters are summarized in Table 5.2.

Table 5.2 Open square model intra-cluster parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Intra-cluster rays *K*-factor | 6 dB for LOS ray, 4 dB for NLOS |
| Power decay time | 4.5 ns |
| Arrival rate | 0.31 ns-1 |
| Amplitude distribution | Rayleigh |
| Number of post-cursor rays | 4 |

### User Mobility Model Parameters

As all horizontal directions are equal for this scenario, we can define the same parameters for and in Eq. 4.11. The vertical motion is described by Eq. 4.12. According to [45] the human center mass movement for the usual gait can be described as periodic function with period T = 0.5s with vertical displacement about 3-5 centimeters. Based on this assumptions and taking into account additional vibrations of a hand holding the mobile device we will choose *σz=0.05m*, *τz=1s* and *f0 = 2Hz*. The parameters are summarized in Table 5.3

Table 5.3 Open square model user mobility parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| *σx ,σy* | 1m/s |
| *σz* | 0.05m |
| *τz* | 1s |
| *f0* | 2Hz |

## Outdoor Street Canyon Hotspot Access

### D-Rays Parameters

In the street canyon scenario deployment the UEs grouped on a relatively narrow path, and with two dominant reflected rays in addition to the direct: the ground reflected ray and the wall-reflected ray. All those rays are counted as deterministic and explicitly calculated during the channel modeling.

LOS ray and the ground-reflected ray calculation procedures are specified in Section 4.2.

The wall-reflected ray parameters determined in the same way as ground-reflected, but instead of antenna heights Htx and Hrx the distances between antennas and nearest wall Dtx and Drx are used.



Figure 5‑2 D-rays in street canyon scenario

### R-Rays and F-Rays Parameters

The reflections from various street object, distant walls and second-order reflection are taken into account as random components. The reflections from the trees, lampposts, bus stops, billboards, etc are defined as deterministic reflection from randomly placed objects (Section 4.3.2), the second order reflections and distant walls reflections are taken into account statistically (Section 4.3.1)

The parameters of random objects deployment for R- and F-rays creation are summarized in

Table 5.4: Street canyon model random objects

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Number of objects | 5 |
| Position distribution | Uniform in the Sidewalk and Road area (Figure 2‑6) |
| Road and sidewalk εr | U[1.5 : 8] |
| AoA and AoD | Defined by TX-object-RX path |

The components of channel impulse response statistics derived from the street canyon (outdoor access ultra-high-rate hot-spots) ray-tracing modeling in previous section and from the measurement data.

Table 5.5: Street canyon model R-rays parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Number of clusters, *Ncluster* | 5 |
| Cluster arrival rate, λ | 0.03ns-1 |
| Cluster power-decay constant, γ | 20ns |
| Ray K-factor | 10 dB |
| AoA | Elevation: U[-20:20˚]  Azimuth: U[-180:180˚] |
| AoD | Elevation: U[-20:20˚]  Azimuth: U[-180:180˚] |

### Intra-Cluster Parameters

The cluster parameters for the street canyon model D-rays and R-rays are shown in Table 5.6

Table 5.6: Street canyon model intra-cluster parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Post-cursor rays *K*-factor, *K* | 4 dB (NLOS only) |
| Post-cursor rays power decay time,** γ | 4.5 ns |
| Post-cursor arrival rate,**λ | 0.31 ns-1 |
| Post-cursor rays amplitude distribution | Rayleigh |
| Number of post-cursor rays, *N* | 4 |

### User Mobility Model Parameters

In this scenario we have one dominant direction of user movement in horizontal plane, so the probability of velocity component across the street is much lower than along the street. Horizontal and vertical motions are described by in Eq. 4.11 and Eq. 4.12 with parameters summarized in Table 5.7

Table 5.7 Street canyon model user mobility parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| *σx* | 1m/s |
| *σy* | 0.1m/s |
| *σz* | 0.05m |
| *τz* | 1s |
| *f0* | 2Hz |

## Large Hotel Lobby Scenario

### D-Rays Parameters

The 3D channel model for hotel lobby scenario should include up to second order reflection rays as D-rays, calculated on the base of method of images and the Fresnel equations, or using ray-tracing algorithm as for indoor legacy 802.11ad scenarios (see Section 3).

Figure 5‑3 illustrates the process if D-rays calculation for Large Hotel Lobby scenario

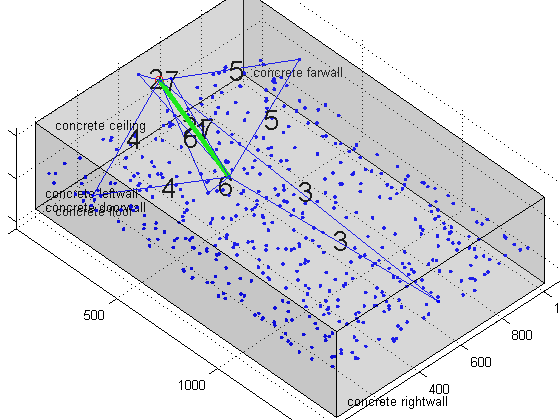


Figure 5‑3: D-rays in Large Hotel lobby scenario (only 1st order reflections shown)

### R-Rays Parameters

R-rays represent reflections from other objects in the room that is not explicitly described in the scenario. The parameters of R-rays in the Hotel lobby channel model are summarized in Table 5.9.

Table 5.8: Hotel lobby model random rays parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Number of clusters, *Ncluster* | 5 |
| Cluster arrival rate, λ | 0.01ns-1 |
| Cluster power-decay constant, γ | 15ns |
| Ray K-factor | 10 dB |
| AoA | Elevation: U[-80:80˚]  Azimuth: U[-180:180˚] |
| AoD | Elevation: U[-80:80˚]  Azimuth: U[-180:180˚] |

### Intra-Cluster Parameters

The intra cluster parameters for indoor access scenario are taken directly from the corresponding indoor scenario, developed in [4] and are based on the experimental measurements [33].

Table 5.9: Hotel lobby (indoor access large public area) model intra-cluster parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Post-cursor rays *K*-factor, *K* | 10 dB |
| Post-cursor rays power decay time,**γ | 4.5 ns |
| Post-cursor arrival rate,**λ | 0.31 ns-1 |
| Post-cursor rays amplitude distribution | Rayleigh |
| Number of post-cursor rays, *N* | 6 |

### User Mobility Model Parameters

As all horizontal directions are equal, we can define the same parameters for and in Eq. 4.11. For this scenario static users are more typical, so values for *σx ,σy* are very low and the verical component of velocity vector is absent.

Table 5.10 Hotel lobby (indoor access large public area) model user mobility parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| *σx, σy* | 0.1m/s |
| *vz* | 0 |

# Ultra Short Range Channel Model

## Ultra-Short Range Scenarios

The ultra-short range (USR) communications scenario covers the usage models where the transmitter and receiver are very close to each over, literally “in tough” with each other. The typical distance for USR is less than 10 cm. The usage models covered are ultra-high speed synchronization and video content downloading in the special sync-and-go kiosk or even metro/transport terminals.

## Experimental Measurements Results

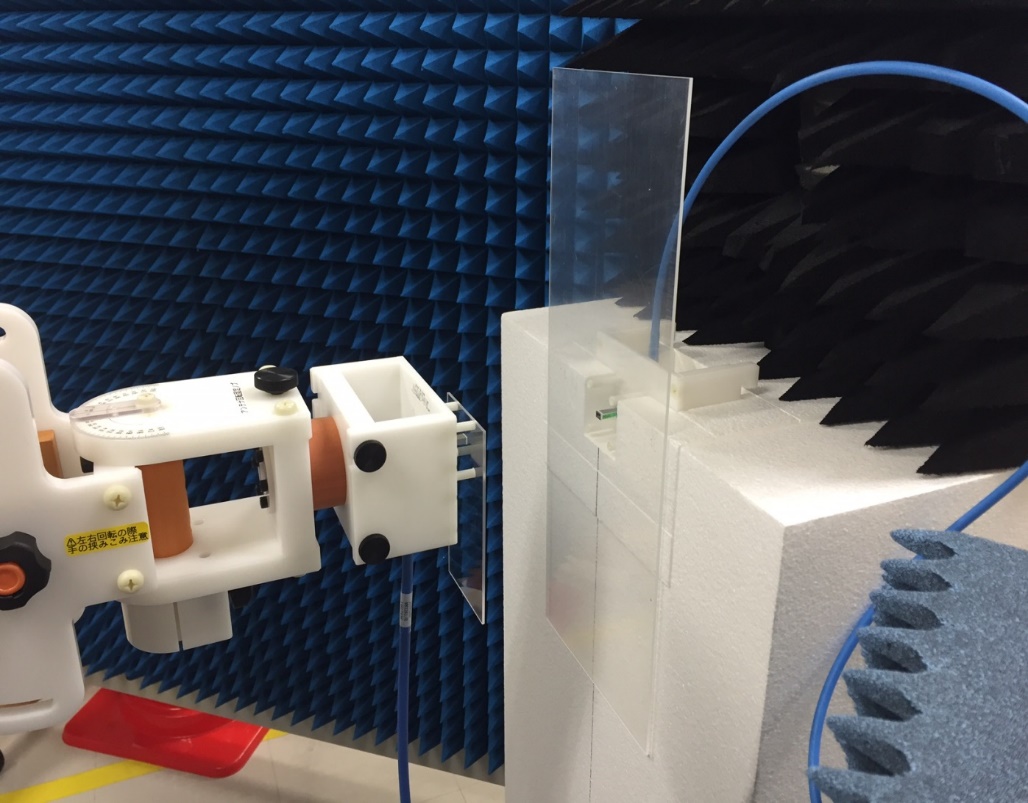
The USR scenario experimental measurements were performed by Panasonic in the framework of IEEE 802.11ay channel modeling activity [46].

### Experimental Setup Description

As an example of USR communications, the link between the ticket gate and the smart phone is considered. For channel measurements, the following setup were used (see Figure 6‑1 and Table 6.1):

* Signal generation and analysis: 2-port network analyzer in 56.28~66.84GHz
* TX and RA: 7.43dBi horn antennas
* Metal and Nnn-metal plates were attached to Tx antenna and Rx antennas for refection effect investigation
* RX antenna position changed to investigate area effects





Tx/Rx Antenna

Plate

Rx

(Smart Phone)

Tx

(Ticket gate)

Plastic stay

Plastic stay

Styrofoam

stand

Figure 6‑1 Experimental setup

Table 6.1. Experimental measurements parameters

|  |  |  |
| --- | --- | --- |
| **Item** | | **Value** |
| Tx power | | 6dBm |
| Frequency | Center | 61.56GHz |
|  | Span | 10.56GHz (4 channel bandwidth) |
|  | Step | 20.625MHz (=10.56GHz/512) |
| Antenna | Type | Horn |
|  | Gain | 7.43dBi |
|  | HPBW | 133.3deg.(E), 83.2deg.(V) |
|  | Aperture size | 5.12mm |
|  | Polarization | Vertical polarization for both Tx antenna and Rx antenna |
| Measurement range | | X:10cm (fixed), Y:-15cm~15cm, Z:-30cm~30cm |
| Measurement step | | 1cm |
| Material of plate (Tx, Rx) | | Metal (Aluminum, Aluminum)  non-Metal (Acrylic, Polycarbonate) |

### Main Results and Interpretation

The experimental results may be presented in the form of the channel impulse response curves for different TX and RX antenna relative positions: see Figure 6‑2 and Figure 6‑3.

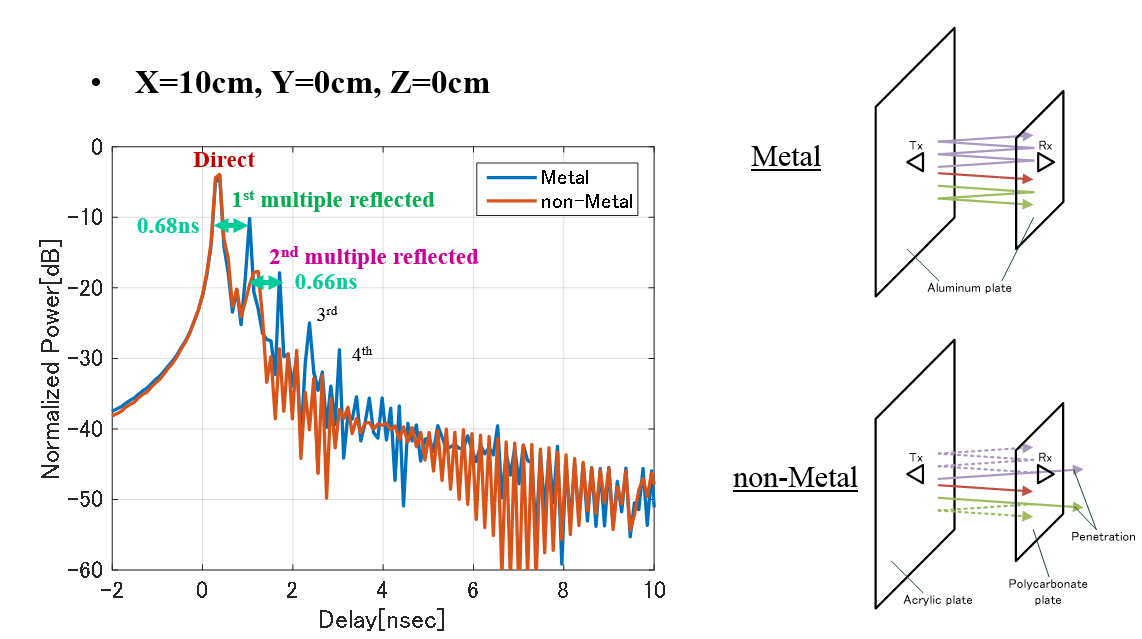


Figure 6‑2. Measurements setup and CIR for x= 10cm, Y = 0cm, Z = 0cm

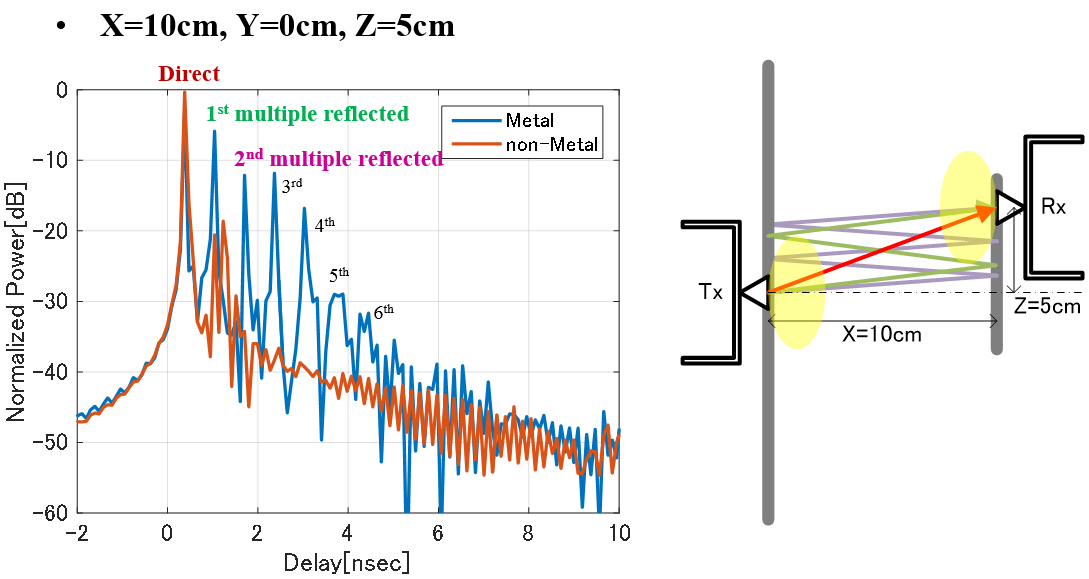


Figure 6‑3. Measurements setup and CIR for x= 10cm, Y = 0cm, Z = 5cm

For the initial theoretical analysis consider the co-aligned antennas positions (Y = 0, Z = 0) with distance between them X = 10 cm (see Figure 6‑2 )

Along with the channel impulse response, measured in the experiments, let’s plot the following curves:

Red: free space propagation with the same delay/ path distance

Blue: Propagation model that includes reflections from both TX and RX surfaces with pre-defined reflection coefficient R

Black: The linear (in log scales) approximation, typically called exponentially decaying power delay profile

(6.1)

Figure 6‑4 shows the experimental results for metal-metal measurements case, along with the auxiliary curves.

It can be seen that the Free-space plus reflection envelope curve with R = 1.5 dB accurately predicts peak positions for the considered case. However, the values below 30-35 dB below the main peak are not significant in the simulations, and only 4-5 peaks (reflections) may be taken into account.

In that case, the linear (in log scale) approximation (6.1) may be use. The basic fitting on the first 5 peaks yields the γ equal to 0.45 ns.



Figure 6‑4 Metal-metal case measurement

The delays of the peaks are very accurately can be described by the multiple reflection model and exactly corresponds to travel distance equal to 10, 30, 50, 70 and 90 cm (0.33 ns, 1.0 ns, 1.67 ns, 2.33ns, 3ns).

The relative shift of the TX and RX along the Y or Z axis will lead to the increase of the delays in accordance with the geometry (see Fig TBD)

The Plastic-Plastic case is also well-aligned with the described theoretical analysis, although the reflected rays peaks are not always clearly visible (see Figure 6‑5)



Figure 6‑5 Plastic-Plastic case measurements

From the theoretical analysis the following facts that may be used for USR model creation can be derived:

* The power of the strongest LOS ray accurately calculated on the base of Friis equation for free-space propagation (far-field case) from the TX-RX distance
* The number of significant rays in worst case of metal-metal reflection is 5, and can be lower for plastic case
* The exponentially-decaying PDP model is accurately describe the experimental data for first 5 rays with corresponding gamma parameter fitting.
* The ray delays are fully determined by the TX-RX distance *d* as *d/c, 3d/c, 5d/c* etc for the aligned antennas and with some geometry-based adjustments for case of shifted antennas placement.
* The angular parameters, such as AoA and AoD can be derived from the geometry

It can be seen that the TX-RX distance (and shift) is the main input parameter of the model and the model can be fully derived from this parameter only.

For the link-layer simulations, it is recommended to use some statistical channel description, which can be based on pre-defined distribution of the TX-RX distance.

The system level simulations, which should take into account the accurate relative TX RX positions and angular parameters seems to be not needed in such simple scenario as USR.

### Channel Non-Stationarity

**TBD**

## Ultra-Short Range Model

The static channel impulse response generation is done by the following steps:

* For every channel realization, determine the TX-RX distance *d* as random uniformly distributed value in range [3, 10] cm
* Determine main ray power Pr from the free-space propagation equation:

,

where Pt is the transmitted power, Gt and Gr are transmit and receive antenna gains, λ is the wavelength.

In case of normalized CIR generation this step can be omitted.

* Determine delays of 5 rays in CIR dividing the ray travel path by the light speed *c*.
* Determine the power of rays as

For metal surfaces case, γ =0.45 ns, for plastic surfaces case γ =0.24 ns

# D2D Communications Channel Model

The D2D channel model described in this chapter is motivated by the “Augmented Reality/Virtual Reality Headsets and Other High-End Wearables” use case from [2]. A good evaluation scenario for this use case is a commuter train during rush hour, where a large percentage of passengers have active personal area networks (see Figure 7‑1). The evaluation methodology for this scenario is described in [6].

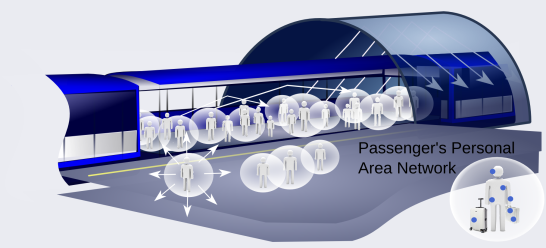


Figure 7‑1 Commuter train sample environment

Ray tracing (RT) and experimental studies indicate that at mmWave frequencies the human body often blocks the LOS path between PAN nodes [47]. However, bystanders and other objects in the environment can act as signal reflectors creating NLOS paths, which are often strong enough to support communication. This is good news except in *dense* PAN deployments, where NLOS signals from unintended transmitters can create significant interference (see Figure 7‑2).

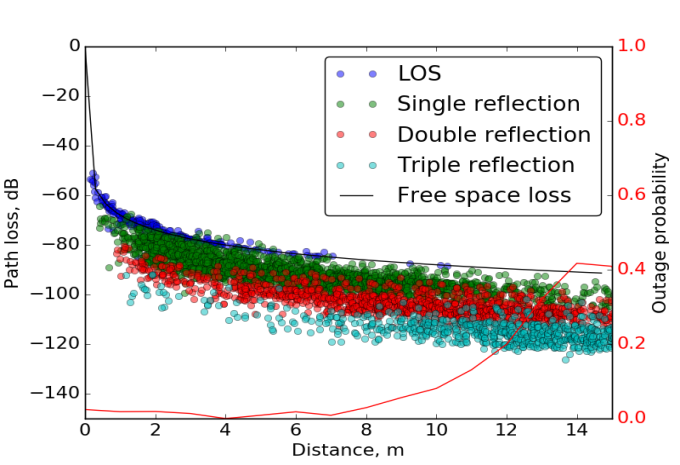


Figure 7‑2 Path losses for various channels in wearable D2D scenario

Due to the many NLOS paths (both intended and interfering) that must be accounted for in dense PAN deployments, the number of surfaces required to model the channel using a quasi-deterministic approach can quickly become unmanageable, thus faster stochastic models are preferred. Furthermore, in the quasi-deterministic channel models discussed in chapter 4 of this document, R and F rays do not represent end-to-end paths (i.e. TX rays do not “map” to specific RX rays), which makes it challenging to assign specific antenna gains to a given TX-RX path.

The model proposed in this chapter is suitable for stochastic generation of spatially consistent, end-to-end radio propagation paths. It uses RT to initially map out the sample environment, and then applies stochastic modelling to reproduce paths between a specific TX and RX based on statistics from the original RT data.

## Overview of Model

The D2D channel model produces outputs that are *statistically* *equivalent* to those acquired via RT for environments that are sufficiently random and isotropic (i.e. all relevant multi-path statistics are preserved, however specific paths such as “the path that reflects off the ceiling” are not strictly identified).

The model takes into account LOS paths (1-hop), single-reflection paths (2-hop), and double reflection paths (3-hop) as these comprise over 95% of usable signal paths. For a given TX/RX input pair, the model outputs the dominant multi-path components between them, where each component is defined by its trajectory, signal attenuation and propagation delay. This output can be easily converted into a channel impulse response subject to a particular antenna pattern as explained in section 4.6 and references therein.

### Common Notations

The following notation is used in this chapter:

* : TX and RX 3D coordinates, respectively
* D: directional vector connecting TX and RX ()
* d: linear TX-RX distance ()
* i: index of path type; is a 1-hop LOS path, is a 2-hop NLOS path, etc.
* : seed values for path type *i*
* : correlation matrix for path *i*
* : correlation distance for path type *i*
* : vector of non-negative integers associated with each type *i* trajectory between the TX and RX
* : length of vector

### Functional Blocks

A flow diagram of the D2D channel modelling procedure is shown in Figure 7‑3. The model is based on RT data of the sampled environment.

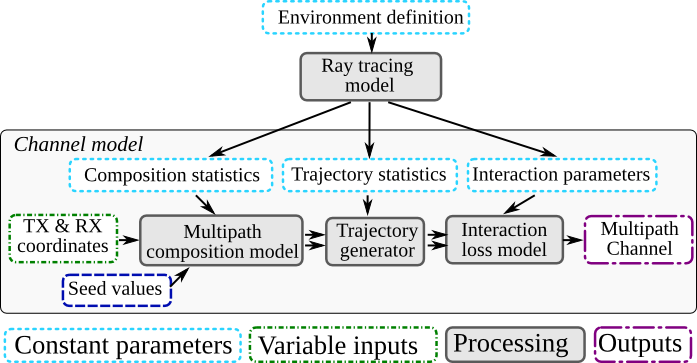


Figure 7‑3 D2D channel modeling procedure

The environment statistics used by the model are as follows:

* Channel composition statistics
  + mean, , and variance, , of the number of paths of each type *i* = 1, 2, and 3 (i.e. 1-hop LOS paths, 2-hop NLOS paths, and 3-hop NLOS paths) between the TX and RX as a function of the distance, *d*, between them;
  + correlation distance, , for each path type *i,* where correlation distance is defined as the average distance the TX and/or RX can move while a specific path exists between them[[2]](#footnote-2).
* Trajectory statistics per path type *i*:
  + correlation between the 1st segment (a directional vector) of a trajectory and the directional vector *D* connecting the TX and RX
  + for *j* = 2 thru *i*, correlation between the *j*th segment and all previous segments along the trajectory
* Interaction statistics:
  + mean value of various material properties for objects encountered along each path type *i* (e.g. for 2-hop paths, what is the mean relative permittivity of objects encountered at that interaction/reflection point).

The D2D channel model takesTX and RX coordinates as input, determines the multipath composition of the channel between them (how many paths of each type exist), generates each path’s 3D trajectory, and assigns path losses. While these are calculated stochastically based on the sample environment statistics, the model is deterministic with respect to the TX/RX input coordinates (subject to constant *seed values*).

In order to convert the resulting multipath channel into a Channel Impulse Response (CIR), one needs to apply the relevant antenna and receiver effects, as explained in the section 4.6.

## Implementing Model

The internal structure of the model is shown in Figure 7‑4, and further explained below.

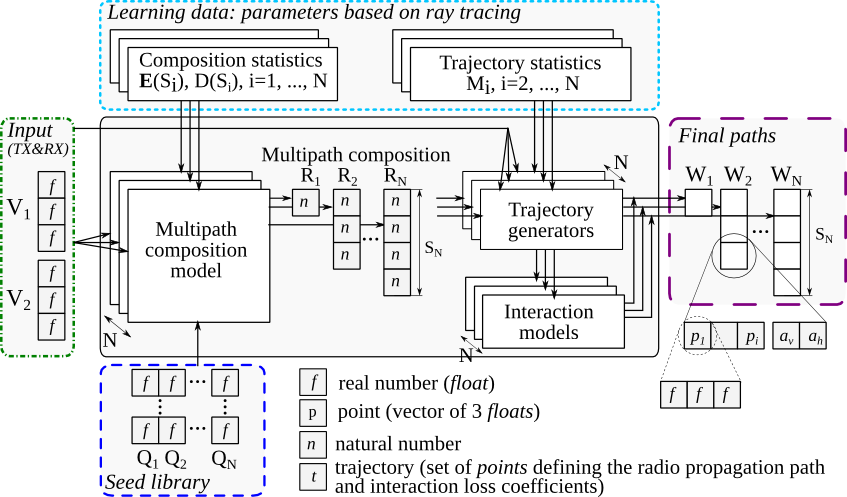


Figure 7‑4 Detailed internal structure of the model

### Multipath Composition Model

For each path type *i*, the multipath composition model *uniquely maps the input* *TX and RX coordinates to a vector* *of unique, non-negative integers, each of which represents a unique type i path between the TX and RX (see* Figure 7‑5*).* Thus, the length, , of equals the total number of type *i* paths between the TX and RX. The distribution of for a given TX-RX distance matches that of the sampled environment.

Figure 7‑5 Multipath composition model

When input to the trajectory generator, a non-negative integer, *k*, results in a specific trajectory connecting the Tx and Rx. Since the trajectory generator function is *deterministic*, the elements of vector must be unique in order to produce unique type *i* paths between the TX and RX. Moreover, in order to maintain the statistics of the sampled environment, they must satisfy the following:

* The probability that the elements of remain the same as the TX moves from coordinate to , where , is no less than 0.5;
* Conversely, if the probability that the elements of remain unchanged is much less than 0.5;
* Obviously, the same concept applies to changes in the RX coordinate, .

For these conditions to hold, we must choose the elements of in a systematic way that preserves the statistics of the sample environment. We do so as follows:

- **Let = [ ],** where *i* = 1, 2, or 3 is the path type (i.e. 1-hop, 2-hop, or 3-hop),

- **For *k* = 1, 2, …** ,

where , is the length of vector , and *d* is the TX-RX distance,

- **Let = [** **if**   **= 1,**

where ρ is the square wave function[[3]](#footnote-3) ,

are the TX and RX coordinates,

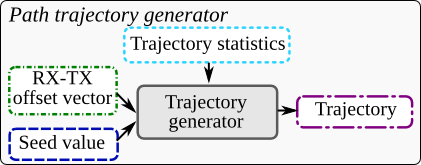
is a seed value (note: the matrix is generated prior to use of the model),

is the correlation distance of type *i* paths in the sample environment,

and is the probability that a given value of *k* will be an element of .

Based on this definition, iffor somevalue of *k*, then when the TX or RX moves (i.e., when or changes, thus *d* changes), remains 1 with a probability that decreases *roughly* linearly with Δ*d*/. In other words, if two TX/RX pairs are close in location, they will likely have identical vectors, thus identical channel multi-path compositions.

### Trajectory Generator

The individual trajectories associated with each element of the vectors are determined as follows (see Figure 7‑6):

#### Trajectory associated with (i.e. 1-hop LOS path)

Figure 7‑6 Path trajectory generator block

is either empty or equal to 1. If empty, there is no LOS path between the TX and RX. If equal to 1, the LOS trajectory is simply the directional vector, *D*, connecting the TX and RX.

#### Trajectories associated with and (i.e. 2-hop or 3-hop NLOS paths)

For NLOS paths, the trajectory generator ensures that:

* The distribution of angles between sequential segments along a trajectory reflects the corresponding distribution in the RT results used to parameterize the model;
* For the same TX/RX pair and path type *i*, different *k* values (i.e. seeds) result in different trajectories;
* Small changes in the directional vector *D* connecting the TX and RX result in small changes in the generated trajectories.

To create a specific trajectory from an element (i.e. k value) in or , we begin by creating correlation matrices based on the ray-traced trajectories from the sample environment as follows:

* Let

where is the path type

and are the TX and RX coordinates of the *n*th ray-traced type *i* trajectory

are the [x y z] coordinates of the *j*th interaction point along the *n*th ray-traced type *i* trajectory (where *j* = 1 to *i*-1)

is a matrix of size *n* x 3\*(*i*+1). Each row represents a different ray-traced type *i* trajectory. Column 1 is vector D of each trajectory. Column 2 is the 1st segment of each trajectory. Column 3 is the 2nd segment. Column 4, which only exists for type 3 trajectories, is the 3rd segment.

* Let ,

where is the Cholesky decomposition of the covariance matrix of .

* has the property that for any random vector x (composed of normally distributed random numbers with zero mean and unit variance), vector has the *same* statistical properties as the trajectories in . However, it does not yield the specific *D* vector required for the given TX/RX locations.

Thus, we create a vector *x* of size 3\*(*i*+1) using a normally distributed random number generator with seed = *k*, then update the first three values of *x* as follows:

This guarantees that the vector connecting the endpoints of trajectory *y* equals the desired vector *D* (i.e. ).

* Finally, trajectory .

### Modelling Path Losses

Once we have determined which trajectories exist between a given TX/RX pair, we must determine their associated path losses:

* Free space loss (according to isotropic radiator antenna model at both ends);
* Free space propagation delay;
* Energy losses associated with reflections from environment.

Reflection losses can be approximated based on Schlick’s approximation in [49]:

where is the angle of incidence, and are the optical densities of the materials.

### Simplifications for Multi-Antenna System Modelling

If multiple TX or RX antennas are present in proximate locations (such as within an antenna array), one could significantly reduce the modelling effort by allowing all of the antennas to share the same *multipath channel composition.* Then, the trajectories generated for each antenna would be based on the same seed values for trajectory generators, but still reflect the location differences among the individual antennas. In this way, a complex MIMO system could be modelled very efficiently without the effort required to run the multipath composition model for each antenna element combination.

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1. Mandatory and optional classification is applied for channel modeling only. [↑](#footnote-ref-1)
2. Note this definition of correlation distance is different from the commonly used coherence distance for channels. [↑](#footnote-ref-2)
3. More efficient implementations of square wave are available [↑](#footnote-ref-3)