P802.11  
Wireless LANs

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| Channel Models for IEEE 802.11ay | | | | |
| Date: 2015-09-12 | | | | |
| Author(s): | | | | |
| Name | Affiliation | Address | Phone | email |
| Alexander Maltsev | Intel | Turgeneva str., 30,  Nizhny Novgorod, 603024, Russia | +7-831-2969461 | alexander.maltsev@ intel.com |
| Artyom Lomayev | Intel |  |  |  |
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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.

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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].

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 11ay 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 new Quasi-Deterministic (Q-D) methodology for channel modeling are introduced and the main results of new experimental measurements are discussed. 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 IEEE 802.11ay use cases, evaluation scenarios, channel models requirements, 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. Following Sections V - VIII describe the new channel models developed for IEEE 802.11ay. Section IX concludes the document.

# Channel Model Requirements

## TGay Use Cases and Evaluation Scenarios

TGay proposes a variety of 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 supplemented with docking station scenario proposed in [3] is 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 proposed 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.

## Channel Model Requirements

## Legacy Indoor Channel Models Extension

## New TGay Channel Models

# MIMO Extension for Legacy 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 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. This document 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. 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. The space-time CIR function defined in section 2.2 of the IEEE 802.11ad channel model document [4] is written 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 technology can be applied. Assuming that one can introduce its own antenna technology and beamforming algorithm over the developed channel model.

The theoretical equation describing CIR after application of beamforming is provided in section 6.1 of the channel model 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.

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. Note 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 and receive 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.

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 transmit and receive channel phasor vectors describing plane wave introduced for one dimensional linear array can be simply generalized for the case of two dimensional planar array.

Figure 3‑2 shows 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 spatial 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 **Vich** and **Uich** 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.

Substituting vectors **Vich** and **Uich** into eq. (3.12) one can obtain:

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

The channel matrix in eq. (3.13) 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)*.

Note that matrix defined in eq. (3.13) 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:

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

Generalizing the eq. (3.13) for 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 departure and time of arrival one can write the following equation:

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

where δ() is a delta function and *Nrays* defined the number of rays in the channel matrix. The eq. (3.15) 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 the eq. (3.15) 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. (3.15) defines a general structure of the channel before beamforming application for the PAA. It represents in the 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. (3.15) is reduced to the scalar case as follows:

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

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. (3.15) is a counterpart of the eq. (3.1) and eq. (3.16) is a counterpart of the eq. (3.2) introduced above for the case of the Phased Antenna Array (PAA) technology.

### General Channel Structure with Polarization Support

The equations introduced in the previous section describe Channel Impulse Response (CIR) 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 reference [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.

A 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 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:

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

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 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:

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

where **eTX** and **eRX** 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. (3.15) describing CIR for Phased Antenna Array (PAA) can be modified to support polarization properties modeling as follows:

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

where **H(i)** is a 2 x 2 polarization matrix for ray with index i, **eTX** and **eRX** 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 CIR after application of beamforming at both ends of the link with polarization support can be defined as follows:

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

where **V** and **U** are transmit and receive AWVs accordingly, **eTX** and **eRX** 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 SU-MIMO Configurations

This section generalizes the channel description for Phased Antenna Arrays (PAAs) introduced in the previous section to support 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:

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

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. (3.21) 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:

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

where **hMIMO i** is a MIMO matrix for *i*-th ray introduced in eq. (3.21), *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:

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

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. (3.22).

### 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 accordingly. 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 distance d1/d2. The experimental results provided in reference [9] shows that the PAAs space 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:

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

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. Note that the eq. (3.24) 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. (3.22).

### 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:

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

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, (**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. (3.22).

### 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:

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

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. (3.22).

### 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. 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. (3.15) 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. (3.16).

### Support of SU-MIMO Schemes

The SU-MIMO schemes summarized in the Table 3.2 use the PAA with single or dual polarization and 2 PAAs at each TX/RX side of the communication link. As it was discussed in Section 3.1.2 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:

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

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 recalculation of the ray angular coordinates is done similar to that discussed in the previous section. The distance between the geometrical centres of the PAAs d is defined as a parameter and can be changed.

### Support of Beamforming Algorithm

TBD

# Quasi-Deterministic (Q-D) Channel Modelling Methodology

## Q-D Channel Modelling Methodology Development

## Experimental Channel Measurement Results

# Channel Model for Open Area Outdoor Hotspot Access

The university campus channel model represents the scenario with large open areas with low and rare buildings like university campus, park areas, city squares.

## Modelling Scenario



Figure 5‑1: Open Area Outdoor Hotspot Access Scenario

## Measurement Results and Ray Tracing Modelling

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## Channel Model Description

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## Polarization Impact Modelling

## Path Loss Model

# Channel Model for Outdoor Street Canyon Hotspot Access

The street canyon (outdoor access ultra-high-rate hot-spots) channel model represents typical urban scenario: city Street with pedestrians’ sidewalks along the tall long buildings. The access link between the APs on the lampposts and the STAs at human hands is modeled in this scenario

## Modelling Scenario

The geometry of the street canyon access scenario that is used for channel model parameters evaluation via ray-tracing simulations is shown in Figure 6‑1. The corresponding numerical parameters are summarized in Table 6‑1.



Figure 6‑1: Street canyon (outdoor access ultra-high-rate hot-spots) scenario

Table 6‑1: Street canyon (outdoor access ultra-high-rate hot-spots) 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 |
| Road and sidewalk roughness σg (standard deviation) | 0.2 mm |
| Building walls material | concrete |
| Building walls εr | 6.25+0.3j |
| Building walls roughness σw  (standard deviation) | 0.5 mm |

## Measurement Results and Ray Tracing Modelling

## Model Development Methodology

## Channel Model Description



Figure 6‑2: Street canyon (outdoor access ultra-high-rate hot-spots) scenario reflected rays illustration

## Model of Dynamical Human Blockage and Doppler Effect

## Polarization Impact Modelling

## Path Loss Model

# Channel Model for Large Hotel Lobby Scenario

The hotel lobby (indoor access large public area) channel model represents typical indoor scenario: large hall with multiple users within. Similar indoor channel models were considered in the [4], with statistical approach to the channel modeling, suitable for link layer simulations. The proposed here quasi-deterministic approach based on the specified STA location and may be used also for the system level simulations.

## Modelling Scenario

The basic parameters and geometry are summarized in Table 7‑1 and illustrated in Figure 7‑1:

Table 7‑1: Hotel lobby (indoor access large public area) scenario parameters

|  |  |
| --- | --- |
| Parameter | Value |
| AP height, Htx | 3.5 m |
| AP position | Middle of the nearest wall  (see Figure 7‑1 ) |
| STA height, Hrx | 1.5m |
| Room height | 4 m |
| Room width | 10 m |
| Room length | 15 m |
| Floor material | Concrete |
| Floor εrf | 4 + 0.2j |
| Floor roughness σf (standard deviation) | 0.1 mm |
| Walls material | Concrete |
| Walls εrw | 4 + 0.2j |
| Walls roughness σw (standard deviation) | 0.2 mm |
| Ceiling material | Plasterboard |
| Ceiling εrc | 6.25+0.3j |
| Ceiling roughness σc  (standard deviation) | 0.2 mm |



Figure 7‑1: Hotel lobby (indoor access large public area) scenario

## Measurement Results and Ray Tracing Modelling

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## Polarization Impact Modelling

## Path Loss Model

# Channel Model for Street Canyon Backhauling

## Modelling Scenario

## Measurement Results and Ray Tracing Modelling

## Model Development Methodology

## Channel Model Description

## Polarization Impact Modelling

## Path Loss Model

# References

1. IEEE doc. 802.11-14/0606r0, Next Generation 802.11ad: 30+ Gbps WLAN, C. Cordeiro, et al., May 2014.
2. IEEE doc. 802.11-15/0625r2, IEEE 802.11 TGay Use Cases, Rob Sun, et al., May 2015.
3. IEEE doc. 802.11-15/0830r0, Docking Usage Model, T. Solomon, July 2015.
4. IEEE doc. 802.11-9/0334r8, Channel Models for 60 GHz WLAN Systems, A. Maltsev, et al., May, 2010.
5. IEEE doc. 802.11-10/0854r3, Implementation of 60 GHz WLAN Channel Model, R. Maslennikov and A. Lomayev, May 2010.
6. IEEE doc. 802.11-15/0866r1, TGay Evaluation Methodology, G. Venkatesan and L. Cariou, July 2015.
7. IEEE doc. 802.11-15/1145r0, SU-MIMO Configurations for IEEE 802.11ay, September 2015.
8. IEEE doc. 802.11-10/0112r1, H. Sawada, Intra-cluster response model and parameter for channel modeling at 60 GHz (Part 3), January 2010.
9. IEEE doc. 802.11-15/0632r1, “Experimental Measurements for Short Range LOS SU-MIMO,” A. Maltsev, May 2015.
10. “Impact of Polarization Characteristics on 60 GHz Indoor Radio Communication Systems,” Antennas and Wireless Propagation Letters, A. Maltsev et al., vol. 9, pp. 413 - 416, 2010.

1. Mandatory and optional classification is applied for channel modeling only. [↑](#footnote-ref-1)