**IEEE P802.15**

**Wireless Personal Area Networks**

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| Abstract | This CMD contains descriptions of the measured propagation characteristics and the associated channel models applicable for the operational environments relevant for the considered applications. | |
| Purpose | The purpose of this CMD is to support the development of IEEE 802.15.3e by providing the methodologies to characterize the PHY performance for the considered applications. | |
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Document Overview

This CMD contains descriptions of the measured propagation characteristics and the associated channel models applicable for the operational environments relevant for the considered applications.

It is suggested that the proposed channel models with the defined parameters be applied to the test environment. The CMD will support the evaluation of the PHY proposals submitted to P802.15.3e for consideration by the 15.3e task group (TG3e).

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# Introduction

This document describes the channel models for close proximity point-to-point (P2P) wireless communications at 60 GHz. The channel models are based on the results and analysis of experimental measurements. The goal of the channel modeling is to support the development of IEEE802.15.3e.

The measurement environment is suited for analysis of channel models under the usage scenario of applications described in the 802.15.3e Technical Guidance Document (TGD), 15-05-0109-03-003e [1]. This document proposes a general structure of a new channel model which takes into account the close proximity propagation characteristics for consumer electronics (CE) devices. The channel model is proposed in accordance with the usage scenarios of file exchange, kiosk download services, wireless storages, and ticket gates.

We describe the channel model on the millimeter-wave band of 57–66 GHz with support for single-input single-output (SISO) and multiple-input multiple-output (MIMO) systems. The MIMO system studied in IEEE802.15.3e can be considered to be a spatially multiplexed system. The channel model for MIMO systems are an extension of the channel model for SISO systems.

In this document, we show the channel model with defined parameter set which measurement analysis are result in. It is suggested that the proposed channel model be extended to the test environment to support the evaluation of the PHY proposals submitted to P802.15.3e for consideration by the TG3e.

This document is organized as follows. Section 2 gives an overview of the usage scenario based on technical requirements and guidance; Section 3 defines the channel model characterization; Section 4 shows the measurement results of power delay profiles under close proximity P2P wireless communications at 60 GHz band ; Section 5 presents an approach to extend channel model of SISO systems to MIMO systems; Section 6 introduces the channel model with defined parameter set based on measurement analysis; Section 7 represents various defined parameter examples of the proposed channel model and a simulation scenario to evaluate PHY performance; Section 8 summarized this document.

# Propagation Environments

With regard to the TG3e Technical Guidance Document [1] and the contribution on application usage [2], environments in where IEEE802.15.3e devices shall be operated can be defined.

The environment of propagation can be assumed to be a line-of-sight (LOS) channel with a short transmission range from about a cm up to 10 cm. Concerning usage scenarios in [1], IEEE802.15.3e transmitters and receivers are implemented inside consumer electronics (CE) devices or infrastructure terminals such as kiosks. Even for a LOS scenario, we need to consider the impact of nearby metallic surfaces such as a metal chassis, a metal cover or a printed circuit board around the transmitters and receivers.

# Channel Model Characterization

The general characteristics of the channel models, the application environments and associated channel modeling parameters are as follows.

## Requirements for channel model

The following are the requirements of the channel models for close proximity P2P communications at 60 GHz.

* Scope close proximity P2P wireless communications with the distance of  
  from millimeter range up to 10 cm;
* Provide accurate space-time characteristics of the propagation channel   
  including the impact of antenna type and CE device;
* Support for SISO systems and MIMO systems;
* Present the impact of antenna polarization at the transmitter and receiver;

## Operating frequency band

The channel characterization shall cover the 57 to 66 GHz range.

## Antenna types

For the purpose of studying the channel models under various usage scenarios, the antenna radiation characteristics of basic antenna types are included. We have chosen a dipole type and a patch type, a waveguide antenna for kiosk, both of which provide a wide radiation pattern suitable for close proximity P2P wireless communications with a touch operation.

## Path loss

For close proximity P2P communications, the transmission distance is limited up to 10 cm. The applicable path loss model is based on the free space loss with a slope coefficient of 2.

(1)

Where *PL* is the path loss, *D* is the distance between the transmitter and receiver, *c*is the speed of light, and *f* is the carrier frequency. *PL* is computed with the mid-band frequency point. The parameter *PL* are derived by eliminating the effects of both Tx and Rx antenna gain.

## Fading / Multipath

For close proximity P2P communications, since the millimeter-wave signals have much shorter wavelengths than for microwaves and lower frequencies, they can be affected not only by objects between the devices, but also by (within) the devices themselves. Particularly at the point of fading or multipath, the effects on the devices can be dominant, since other objects such as walls, ceiling, furniture, and computer peripherals are relatively distant.

Although many measurements of channels in the 60 GHz band and some definitions of channel models have been reported [3]-[9], these cannot truly represent channel models under close proximity wireless conditions. We introduce a channel model which is developed in [10]-[12] to enable their use for 15.3e. In [10]-[12], a simple channel model was proposed under close proximity wireless communications using CE into which millimeter-wave transceivers were implemented.

## Shadowing

For close proximity P2P communications under LOS (line-of-sight) conditions, it is not necessary to take into account shadowing effects on the channel models and simulation criteria.

## Polarization

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

The impact of polarization is substantially higher for close proximity 60GHz than for other communications having a longer transmission distance. The physical reason for the high impact of polarization is that the first-tap signal arrives under LOS conditions and thus remains strongly polarized. On the other hand, the second- or later-tap signals which are reflected against devices suffer from random polarization. Experimental proof of the polarization impact on channel propagation on 60 GHz band was given in [13]-[14]. To support polarization impact on the channel model, polarization characteristics of antennas and polarization characteristics of the propagation channel should be introduced. An approach to introduce polarization characteristics into channel models in close proximity wireless communications on the 60 GHz band was proposed in [10]-[12]. This approach was used as the basis for the development of the polarization model used in this document.

For the simulations of transmission performance, we assume the following two items. The first is that the polarization is aligned between the transmit and receive antennas during communications. The second one is that polarization conditions and antenna orientations of the transmit and receive antennas are not changed during communications.

## Power Delay Profile

The power delay profile (PDP) of a channel is the average power of the channel as a function of an excess delay with respect to the first arrival tap. Each delay can be modeled independently with amplitude and phase variations. In the close proximity transmission, angle of arrival (AoA) can be uniformed for each delay tap.

## MIMO

MIMO (multiple-input and multiple output) transmission described in this document is based on short-range communications where each transmit antenna can broadcast at the same time and in the same bandwidth an independent signal. This corresponds to a spatial multiplexing system. Using this technology with *M* transmit and *M* receive antennas, for example, an *M*-fold increase in data rate can be achieved over the same bandwidth [15][16].

This document shows a set of channel models applicable to MIMO transmission system in IEEE802.15.3e on 60 GHz band. The MIMO channel model is derived by extending the single-input single-output (SISO) channel model described in this document.

## Others

The IEEE802.15.3e system is based on packet-by-packet communications with high throughput which means each packet length is quite short. For such usage scenarios, a CE device having a transmitter or a receiver implemented inside is held by human. Human movement is said to be about up to several hundreds of milliseconds which is relatively longer than each packet length. The parameters of channel model can be derived under the assumption that the channel is static during a packet transfer.

Molecular attenuation on 60 GHz band can be ignored because usage scenario focuses close proximity wireless communication with transmission distance of up to 10 cm.

# Power delay profile measurement and modeling

## Measurement Setup for SISO systems

Figure 1 shows the setup to measure DPDs. The small and flat transceiver modules that we developed [19] are implemented into the consumer electronic (CE) devices of laptop PC and digital still camera (DSC). Each transceiver module consists of a developed 60 GHz transceiver IC and a thin connector. Baseband signals are transmitted between the modules and measuring equipment by using small-gauge coaxial cables. Measuring equipment is located sufficiently far from the electronic devices. The developed IC consists of up/down converters, a power amplifier for Tx, a low-noise amplifier for Rx, and an antenna for Tx /Rx [20]. The antenna is a bonding wire loop antenna having a beamwidth of approximately 60 degrees horizontally and approximately 120 degrees vertically [20]. To measure frequency spectra, an OFDM signal is used. The signal is generated by an arbitrary waveform generator (Tektronix AWG5012C), transmitted via the 60 GHz proximity channel, and sampled by an oscilloscope (Agilent DSO9104A). The frequency spectra across the 56 to 66 GHz range are obtained at intervals of 15.625 MHz by compensating for the frequency characteristics of the measurement system, such as cables and transceivers including antennas. The measured frequency spectra across the 10 GHz band range are converted to power delay profiles (PDP) by using an inverse fast Fourier transform. The Hamming window is used to obtain a large dynamic range.

The measured signal power is affected not only by multi-path fading, but also by loss of propagation. To focus on multi-path fading, the loss component is compensated from the measured data. We confirmed that the propagation loss measured without any objects in the vicinity other than the transceiver modules fits well with the theoretical free space loss.



Figure 1: Measurement setup.

## Measurement Conditions

The measurement environment is set on a desk. A metal board is placed on the desk in order to simulate more severe environment. The CE devices contain not only the transceiver modules but also other pre-existing components, such as substrates, electronic components, and batteries. These components contain metal. The cases of the CE devices themselves also contain metal. The coordinate origin of the measurements is taken to be at the antenna of the transceiver IC in the laptop PC, which lies at a fixed position on the desk. The measurement point (*x*, *y*, *z*) is located at the antenna of the transceiver IC in the DSC. The *X*, *Y*, and *Z* axes represents the horizontal offset, the distance, and vertical offset between the devices, respectively. The DSC is fixed on a three dimensional stage that moves according to programmed procedures. Other objects such as the measuring equipment are covered with radio wave absorbers to reduce their effect on the results. The measurement ranges and other conditions are summarized in Table 1.

Table 1: MEASUREMENT CONDITIONS

|  |  |
| --- | --- |
| Frequency range | 56-66 GHz |
| Frequency step | 15.625 MHz |
| Tx power | 0 dBm |
| Tx electronic device | Laptop PC |
| Rx electronic device | DSC |
| Measurement range | X: 15~15 mm, Y: 10~80 mm, Z:0~6 mm |
| Measurement step | 1.5 mm along X and Z, 0.1 mm along Y |
| Antenna polarization | Horizontal polarization |

## MEASUREMENT RESULTS

This demonstrates that multi-path fading caused by the CE devices does exist. Figure 2 shows averaged PDPs. Averaging was carried out over the range of (*x*, *y*, *z*) = (15~15, 10~40, 0~6) at intervals of 1.5 mm. For comparison, the range of 40~80 mm along the *Y* axis over the same *X* and *Z* ranges was also evaluated. The power of the measured PDP is normalized by total power after averaging. It can be said that PDPs are similar to the conventional exponential decay profile with relatively large power in the first path [21], [22]. It is notable that the two PDPs for different *Y* ranges are quite similar. These prompt the following hypothesis with consideration for the dominant cause of reflections.

Concerning reflections caused by the CE devices, there are two possibilities as illustrated in Figure 3. One is intra-device reflection, which is reflection inside of each CE device. The other is inter-device reflection, which is reflection between the two CE devices. When *d* is the distance between the two facing devices, the length of the inter-device reflection path route tends to be 3 times *d*. The proportional difference causes approximately 9.5 dB fixed propagation loss without depending on *d*. On the other hand, the delay difference between the direct path as the first path and the inter-device reflection path as the second or later paths increases in proportion to *d*. From these observations, the gradient of the exponential decay in PDP would be expected to change depending on *d* if inter-device reflections are dominant. Conversely, this result indicates that intra-device reflections do exist and are dominant under this measurement conditions in Figure 1. Under this hypothesis, it is reasonable for the measured PDPs to be dense in the time domain as shown in Figure 2. Since the CE devices are densely filled with a large number of components, the time difference among intra-device reflection paths can become very small.

Depending on the antenna type, rotation and orientation, including effects of ground planes of printed boards and other components, the reflection characteristics must be changed. Due to iterated measurements, for various kinds of channel environments at 60 GHz, we can state a hypothesis that delayed paths which are reflected a few or more times suffer from dispersive propagation at the point of fading and polarization. We present the verification of the hypothesis with measurement results in the later sections of 4.4 and 4.5.



Figure 2: Measured averaged PDPs

 

Figure 3 : Schematic diagram of intra-device reflections (left) and

inter-device reflections (right) by electronic devices.

## Distribution of received signal power under multipath

Figure 4 shows the cumulative distribution functions (CDFs) of the path power. The power of the path at each excess delay is normalized by the average power. For comparison, a Rayleigh distribution and Rice distributions with 3 dB and 5 dB Rice factors are also shown. With the exception of the CDF of the path at 0.0 nsec, the CDFs fit the Rayleigh distribution well. In accordance with the central limit theorem, the amplitude of the combined path at each delay is Rayleigh distributed if there are a sufficient number of paths. These results support the aforementioned hypothesis; that is, delayed paths which are reflected a few or more times suffer from dispersive propagation at the point of fading. In this case delayed paths are predominantly caused by intra-device reflections. Owing to the short wavelength and the many components in the electronic devices, the intra-device reflections can cause diverse path routes, whereas the inter-device reflections generate paths within a limited range of angles as illustrated in Figure 3. On the other hand, the CDF of the path at 0.0 nsec is similar to the Rice distributions rather than the Rayleigh distribution. This indicates that a line-of-sight path exists and is dominant for the first path.



Figure 4 : Cumulative distribution functions of normalized power of delay paths.

## Impact of Polarization

One plausible explanation is a change of radio wave polarization due to reflections [21],[22]. In general, radio wave polarization is changed by reflection at complex objects. The antenna is horizontally polarized and has about 10 dB loss in vertical polarization [22]. These can cause additional decay. To evaluate the effect, additional measurements were carried out. The Tx transceiver module was removed from the device chassis, i.e. the laptop PC, and placed on a foamed polystyrene block with rotation in 90 degrees. The rotation changes the polarization of the Tx antenna from horizontal to vertical. For comparison, a measurement without the rotation was also carried out. The measurement conditions other than the device chassis for Tx and the rotation were the same as the last measurement. The measured PDPs are shown in Figure 5. In order to compare the relative powers, the power of both PDPs is normalized with respect to the total power of the PDP measured without the rotation. There is a gap between the two PDPs at 0.0 nsec which disappears after approximately 0.2 nsec. This indicates that the radio waves can be quickly depolarized by a certain number of reflections inside the devices. These results also support the aforementioned hypothesis; that is, delayed paths which are reflected a few or more times suffer from dispersive propagation at the point of polarization.



Figure 5: Averaged PDPs with and without rotation of

the transmission antenna in 90 degrees.

## Observation of cluster caused by inter-device reflections

In other types of antenna implementation, measurement results shows clear cluster that is attributed in the inter-device reflections. Figure 6 shows the measured PDP with three ranges of transmission distance. Tx antenna is waveguide type antenna and Rx antenna is microstrip antenna. In this figure second peak is clearly observed.

Positions of second peaks in each curve are changed along with the transmission distance. The second peaks are attributed to the inter-device reflections, whose propagation route is “Transmitted from Tx → reflected on Rx →reflected on Tx →Rx”. The length of the route is three times of the transmission distance; for example, the second peak of the curve for 30 – 50 mm transmission distance is located around 0.25 nsec, which corresponds to the time of around 75 mm propagation, consequently that is close to one round-trip time of 30 - 50 mm inter-device reflections. A inter-device reflection includes intra-device reflections on the way of propagation route, hence it is observed as a cluster.

In this figure, the peak that depends on the transmission distance is only one, in other words the inter-device reflection cluster that have to be considered within this 50-dB dynamic range.

In simulating higher-order modulations, and/or with highly reflective chassis, another cluster should be included.



Figure 6:　Measured PDP

# Approach for MIMO systems

For the purpose to realize channel models for MIMO systems, its approach is based on measurement results in SISO channel response; MIMO channel matrix **H** comprises SISO channel responses as each element.

As described above, in the close-proximity transmission environment, received level of line-of-sight (LOS) components will be large. Therefore MIMO transmission in 3e systems will be LOS-MIMO or short-range MIMO (SR-MIMO). SR-MIMO transmission relies not only on the difference between multipath components but also on the difference in direct wave components of the line-of-sight propagation. Basic idea of SR-MIMO are shown for example, in [17]. In SR-MIMO whose LOS reception level has dominant impact on channel model and is sufficiently larger than the reception levels of multipath components, channel capacity is maximized when the element spacing is optimized. The optimum element spacing can be determined along the transmission distance.

Figure 7 shows the typical structure of the channel of SR-MIMO. Antenna arrays of the transmitter and the receiver are directly faced each other via transmission distance *D*. Geometry of both arrays is the same rectangular array, with element spacing *d*.

Figure 8 shows examples of array arrangement examples for the numbers of elements, *M* = 2, 4, 8, 9, 16 systems. In SR-MIMO, channel capacity is maximized when the element spacing *d* is optimized[17]. Figure 9 shows the optimum element spacing, *dopt*, for arrays shown in the previous figure. In designing the IEEE801.15.3e system with MIMO, antenna arrays will be designed by using the optimum element spacing for the target transmission distance, *D*. The proposer can set any target transmission distance if it is within the scope of this project.



Figure 7: Short-range MIMO channel which comprises *M* = 16 antenna arrays.



Figure 8:Array arrangement examples.



Figure 9: Optimum element spacing calculated geometrically

In actual MIMO transceivers, microstrip antenna will be typically used. Here the validity of the geometrical path length calculation is shown by comparing the result with the measured channel response (Figure 10) [16]. The figure shows the measured difference in path lengths in path Tx element #1 – Rx element #1 (*h*11) and Tx element #1 – Rx element #2 (*h*21). The values are the averages of 201 measured points in the frequency band of 24-26 GHz (as an scale model of 60 GHz band). In this figure the solid line shows the difference in path lengths, which is calculated geometrically. The measured values were found to be close to the calculated ones, thus confirming the validity of the element spacing’s geometrical design. This observation shows that in modeling LOS component of SR-MIMO channel, channel response is close to the free-space propagation which can be calculated geometrically only using the information of array arrangement.



Figure 10: Phase differences vs. element spacing with fixed transmission distance (measured and calculated).

# Channel Characterization

The measured channels are characterized by using the conventional exponential decay profile and an additional parameter ** which denotes an initial decay. By using a decay factor ** and the initial decay **, the path amplitude  at delay time  is given by

(2)

where  is the expectation value and *N* is the number of paths. The first path, , exhibits the Rice distribution with Rice factor *K* dB. Other paths, , exhibit the Rayleigh distribution. For the purpose to represent these propagation paths, tap concept [23][24] is applied in channel model expressions with a function of delay time. Conventionally, the initial decay is expressed in terms of only the Rice factor *K* [25]. In the modified expression, the initial decay ****is defined not only in terms of the Rice factor *K*, but also in terms of the antenna gain of the two polarizations as given by Eq (3). The first tap, other delayed taps and these parameters are illustrated in Figure 11.

** is mainly dependent on the inside of the CE devices. For example, if a CE device contains a lot of metal parts inside, ** can become large. The Rice factor *K* also tends to depend on the device casing material. The inter-cluster decay rate is *Γ*. Intra cluster decay rate for the cluster #*i* is *γi*.　Cluster arrival time is *τi*, which is determined by the transmission distance.

** depends on antenna characteristics of polarization and the Rice factor as given by Eq (3).

(3)

where , , , and  represent the antenna gain in linear scale for horizontally and vertically polarized Tx and Rx, and *K* denotes the Rice factor in dB. The denominator represents the received power if the radio wave is sufficiently depolarized. The numerator represents received power if the radio wave is not depolarized. The numerator also contains a component of line-of-sight expressed by *K*. We assume that the radio waves can be sufficiently depolarized within a minimum time resolution of the target system.



Figure 11: Schematic diagram of the channel model for 60 GHz close proximity

# Model Parameterization

## List of Parameters

The complete list of parameters used in this document can be summarize as follows:

1. *K*, K factor of Rice distributions for the first arrival tap

2. , intra-cluster decay rate for the delayed taps (*i* = 0,1,2,3, …)

3.  initial decay between the first tap and delayed taps

4. *τi*, cluster arrival time

5. *Γ*, inter-cluster decay rate

As simulation scenario, there above parameters are introduced under the conditions that polarizations between the transmitter and the receiver are aligned.

## Model Parameterization for 57 – 66 GHz

Proposer shall report values of parameters that is used in the performance evaluation simulation.

## Simulation Scenario

In this section, we describe how to simulate multipath fading effects on transmission performance of proposed wireless system in IEEE802.15.3e. These scenarios are for reference only; other scenarios which provide the same principle as the following will be admissible.

### Maximum tap space

Regarding signal bandwidth (BW), 15.3e channel models assume that maximum tap spacing can be represented by

, (4)

*where N* 2.

*BW* is assumed to be 1.76 GHz in IEEE802.15.3e, so *tap-space* can be calculated to be 0.2841 nsec. Concerning the case where signal bandwidth is expanded due to channel bonding, tap spacing, *tap-space*, shall be reduced by the factor of 2*Bonding-BW/BW*, where *Bonding-BW* is the new signal bandwidth.

### Number of multi-path

The number of multi-paths varies depending on the environment. Based on initial measurements the number of multi-paths are counted to be about between 1 to 8. We suggest that the number of multi-paths be arranged related to reflective objects around a transmitter and a receiver.

Considering average received power levels of the first tap and delayed taps, we suggest that all the multi-path taps whose level difference is within the value that the proposer determines against the first tap should be included into simulation scenario.

### Impulse response of each path in the first cluster that comprises LOS component

Each tap in Figure 11 of impulse response, *h*, has a Ricean distribution and comprise a fixed and random component. From the reference [23][24], the impulse response can be represented by

The first tap:

(5 a)

Other tap for multi-path :

(5b)

where P is the received signal power of the first tap including direct wave,  is derived from the angle of arrival/departure of the LOS component, *X* is a complex Gaussian random variable with zero mean and unit variance, τd is the delay time of multi-path tap from the first tap.

The K factor only applies to the first tap of the impulse response, all other taps have a K factor of 0. For the 802.15.3e channel model, the angle of arrival /departure of the LOS component can be fixed at some value for example 0 degree.

Equations shown in this subsection have random values, *φ* and *X*, and proposer can run simulations using the averaged impulse responses shown in Figure 11.

### Impulse response for following clusters

Cluster arrival time is *τi* that is defined by the transmission distance.

=0 (6)

### MIMO system

Figure 12 shows the basic model of a MIMO channel. In the figure the number of elements is set to *M* = 2. Antenna arrays at the transmitter and receiver are directly facing each other. Geometry of both arrays is the same, including element spacing.



(a) structure of SR-MIMO channel



(b) Model comprises *M*2 SISO channel responses

Figure 12 : Channel modelling of MIMO system

The model for the impulse response outlined in the above sections represents a SISO model. For a MIMO system, the taps are created for each element of the MIMO channel matrix, **H**. The impulse response, *hij,* can be modified for the *i-*th receive antenna and *j-*th transmit antenna pair, as the following;

The first tap is

(7).

In the form of matrix, the first tap is (here *M* = 2 is assumed in the second line of this equation);

 (8)

**HF** is not time-variable, fixed component. Each element of this matrix is calculated geometrically using the location of each antenna element. *Aij* is the real number which denotes the amplitude of this LOS path, *φij* is the phase rotation due to that path length. When the path length of Tx antenna #*j* and Rx antenna #*i* is *lij*, these values are shown below.

(9)

(10)

As described above, *lij* are calculated geometrically from the antenna arrangement. *f* is the RF frequency.

On the other hand, **Hv** is the component which is independently Rayleigh distributed, i.e., i.i.d. (independent and identically distributed) channel. In the close proximity transmission, transmitting antenna and receiving antenna are located in the same scattering environment unlike wireless LANs or mobile communications, and the element spacing is more than half a wavelength. Hence the MIMO channel model assumes that the multipath component is independently Rayleigh-distributed.

Other tap for multi-path in the first cluster is expressed in the same form as for SISO.

. (11)

As for the following clusters,

=0　　　 　　　　　　　　　　　　　　　　(12)

# Summary and Conclusions

This document has presented the channel model for performance evaluation of IEEE802.15.3e system proposal. The parameters for close proximity P2P system considering file exchange application and kiosk download service were introduced based on measurement data. The channel model also includes the impact of polarization alignment between the transmitter and the receiver for practical usages .

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