A Dynamic 60 GHz Radio Channel Model for System Level Simulations with MAC Protocols for IEEE 802.11ad

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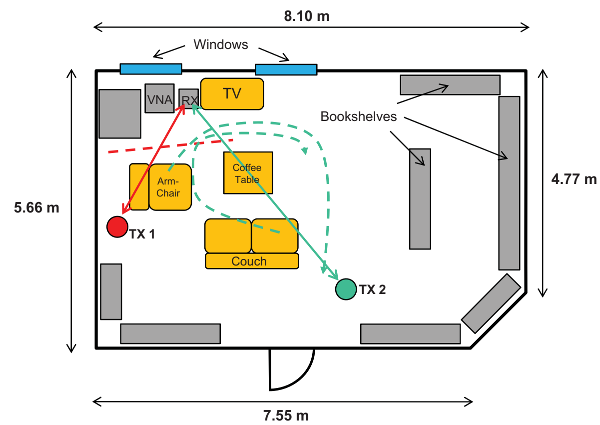
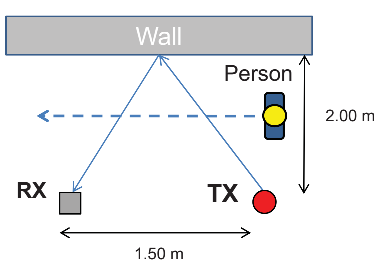
***Abstract*—This paper presents a dynamic 60 GHz radio channel model for system level simulations with MAC Protocols. It is based on radio propagation measurements investigating the influence of moving humans on the 60 GHz channel, which has been performed in the framework of IEEE 802.11ad 60 GHz WLAN standardization.**

I. Introduction

Due to its highly available bandwidth the interest in the license free 60 GHz band for wireless indoor communications is growing worldwide. Emerging applications like high definition video streaming or ultra fast wireless data transfers push the demand for increasing data rates up to several Gbps in next generation wireless local area networks (WLAN). Currently, first mass market products are available, but still different standardization bodies and industry led consortia battle for supremacy [1]–[5]. Nevertheless, important scientific problems have not been fully explored yet. In order to evaluate future 60 GHz WLAN systems during the development process it is important to consider channel dynamics, especially for beamforming systems. In an environment with stationary devices, nonstationarity of the 60 GHz channel mainly appears from moving people. From literature little is known about the characterization of human- induced shadowing events in the 60 GHz band. People may attenuate the communication link by up to 20 dB and more. Other important parameters like amplitude, duration, rising time and occurrence rate of fading events are investigated experimentally and by simulations [6]–[11]. Based on investigations like these, often spatial diversity is proposed to enhance coverage probability. In contrast to the mentioned literature, in this paper the influence of human blockage on single propagation paths is investigated. This is done in order to link the results with cluster-based channel impulse response models. In this approach the signal power from chosen clusters is attenuated according to the temporal characteristics of our model. The resulting model can be used as a dynamic 60 GHz radio channel model for system level simulations with MAC Protocols. In systems with highly directive smart antennas, amongst other things the communication link is established by choosing one single appropriate propagation path in the MAC layer. Usually this will be the direct LOS path, but in NLOS situations it could be, for example, a single reflection from a wall. Measurements have shown that the PHY layer performance will be nearly optimal when using a single cluster, due to flat channel characteristics indicated by low RMS delay spread values (0 - 1.4 ns) [12]. Hence the MAC layer is of special interest. The proposed model is based on radio propagation measurements investigating the influence of moving humans on the 60 GHz channel, which have been performed in the framework of IEEE 802.11ad 60 GHz WLAN standardization [13]–[15].



(a) Schematic of living room scenario with TX/RX positions and walking paths.



(b) Schematic of the conference room scenario with a person crossing a once reflected 60 GHz link.

Fig. 1. Measurement Scenarios.

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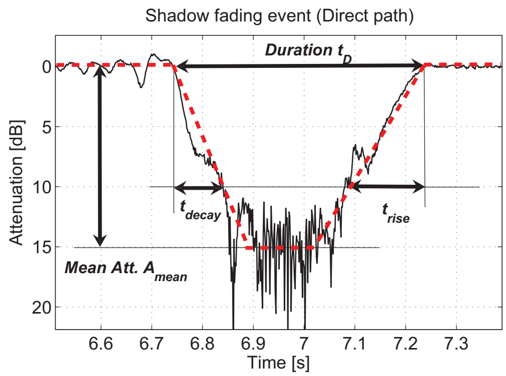
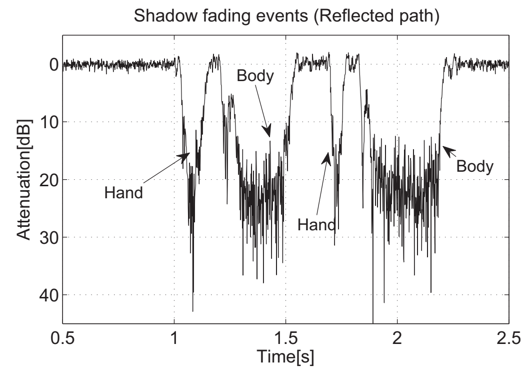


(a) Single human-induced shadowing event with definitions and corresponding model



(b) Human-induced shadowing events influenced by the human body and the swinging motion of the human hand.

Fig. 2. Example for temporal characteristics of human-induced shadowing events in both scenarios.

The paper is organized as follows. Section II describes the measurements and presents the measurement results. Section III proposes a model for human-induced shadow fading events in the 60 GHz range as well as the application of this model to MAC layer simulations. Section IV concludes the paper.

II. Measurements

A. Measurement Setup

The propagation measurements were conducted using an Agilent E8361A vector network analyzer and external transmitting and receiving test heads with WR-10 waveguide flanges. The system has been set up to perform time sweeping with a temporal resolution of 1.3 milliseconds at a single frequency of 67 GHz. For the measurements, vertically polarized circular horn antennas (20 dBi gain) with a half-power beamwidth of 10 degrees have been used at both transmitter and receiver. The small beamwidth has been chosen in order to measure the influence of the person on one single transmission path. All measurements have been observed by video recording.

We have investigated two different scenarios.The first scenario is a living room equipped with typical furniture, where a single person was moving on three different specified walking paths (see Fig. 1a). The receiver position (RX) was kept fixed close to a television during the measurements, whereas two different transmitter positions (TX 1, TX 2) were chosen, both assuring LOS conditions. They were placed at a height of 1.10 meters and a distance of 4.38 meters and 2.58 meters, respectively, to each other. These configurations have been chosen in order to emulate a realistic application scenario where a video streaming device (TX) is connected to a television (RX) and a moving person disturbs the transmission link. In case of a blocked LOS path a reflection at a wall could be used to maintain transmission. This reflected wave in turn can also be disturbed by people. The behavior in this case was to be examined in the second scenario. The setup of this scenario is shown in Fig. 1b. The measurements were carried out in a conference room. Transmitter and receiver were placed at a height of 0.75 meters on a parallel line at a distance of 2 meters to a wall with approximately 10 dB reflection losses. They were separated by 1.5 meters and directed to the specular reflection point at the wall. The person was moving parallel to the wall with different walking speeds and at different distances to the wall.

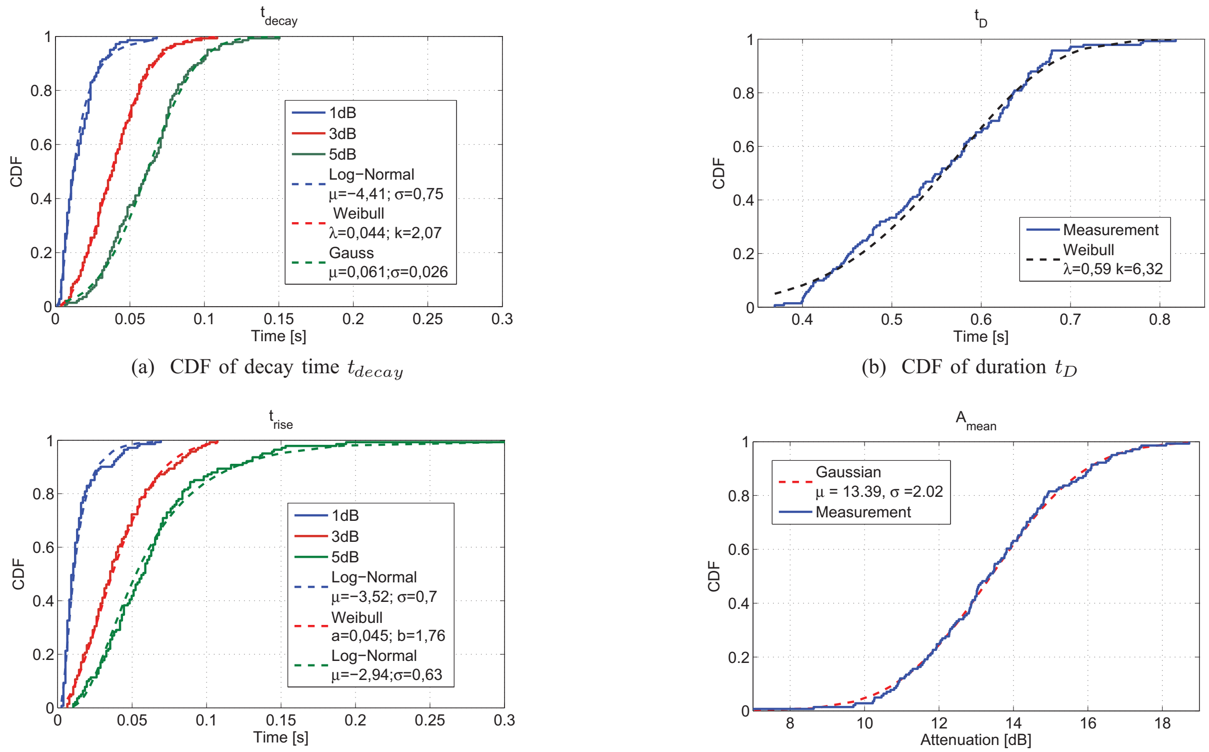
B. Measurement Results

1) Definitions: Fig. 2a shows an exemplary shadow fading attenuation gap obtained from measurements (solid line) in the living room as well as the corresponding shape of the proposed model (dashed line) to describe this event. The video recordings show that the influence of the person on the radio wave propagation begins shortly before the person crosses the path between TX and RX. This behavior can be explained by diffraction around the person. In Fig. 2a, for example, this diffraction causes oscillations with peak-to-peak amplitudes of up to 2 dB before the actual shadowing gap. These values are in good agreement with knife edge diffraction theory [16]. In Fig. 2b, an example for the temporal characteristics of human-induced shadowing in the reflection scenario is shown. Here, a significant difference between the two scenarios can be recognized. The natural swinging motion of the human hand at higher walking speeds causes shorter fading events before the whole body crosses the propagation path. Another reason for distinct visibility of this phenomenon is the fact that TX and RX are positioned at a lower height than in the living room and the radio wave interacts with the person at the height of the swinging hands.

TABLE I
Mean Value of Analyzed Parameters

Parameter	Direct Path	Reflected Path
t_D	550 ms	460/150 ms
A_{mean}	13.4 dB	-
A_{max}	26.0 dB	-
r_{decay}	82.0 dB/s	167.0 dB/s
r_{rise}	76.9 dB/s	217.4 dB/s

Four parameters have been chosen to describe a shadow fading event (see Fig. 2a). The duration t_D characterizes the



(a) CDF of decay time t_{decay}

(b) CDF of duration t_D

(c) CDF of rise time t_{rise}

(d) CDF of mean attenuation A_{mean}

Fig. 3. Cumulative density functions (measurement and model) for the analyzed parameters t_{decay}, t_{rise}, t_D and A_{mean} in the living room.

time between the last zero crossing before and the first zero crossing after the shadowing event. The decay time t_{decay} and the rising time t_{rise} specify the time span between the zero crossings of the signal level and a given threshold (10 dB in the figure) in each case. The mean attenuation A_{mean} is calculated in the interval $[\frac{1}{3}t_D < t < \frac{2}{3}t_D]$ and is based on the received power without the influence of the person. The above mentioned parameters have been statistically analyzed based on several hundred measurements.

2) Living Room: The results for the living room scenario are shown in Fig. 3a-3d) in the form of cumulative probability densities (cdf). The investigations have shown that the drop of signal level happens in the order of tens of milliseconds. In average the signal decreases by 20 dB in 230 ms, whereas it takes 16 (61) ms for a drop of 1 (5) dB. In 90% of the cases the signal decrease took at least 4 ms for a 1 dB, 27 ms for a 5 dB and 101 ms for a 20 dB threshold. The duration of a single fading event amounts to 550 ms in average and the mean attenuation A_{mean} lies between 6 and 18 dB, whereas the maximum attenuation A_{max} (not shown) can amount to up to 36 dB. An overview with the mean values of the analyzed parameters can be found in Table I. Please note that here not the rise time and the decay time are listed, but the slew rates based on a 5 dB threshold:

$$r_{rise} = \frac{5dB}{t_{rise}} \tag{1}$$

$$r_{decay} = \frac{5dB}{t_{decay}}. \tag{2}$$

3) Conference Room: The results for the conference room scenario are shown in Fig. 4 - 5 in the form of cumulative probability densities for t_{decay} and t_{rise} and a probability density function (pdf) for t_D. The cdfs of t_{decay} and t_{rise} are shown for thresholds of 5, 10 and 15 dB. They show similar shape as for the living room, but the slew rates based on a 5 dB threshold are significantly higher here and amount to 167.0 and 217.4 dB/s, respectively. This is caused by the smaller distance between TX and RX, but mainly by a higher walking speed. In the pdf of t_D the influence of the human hand can

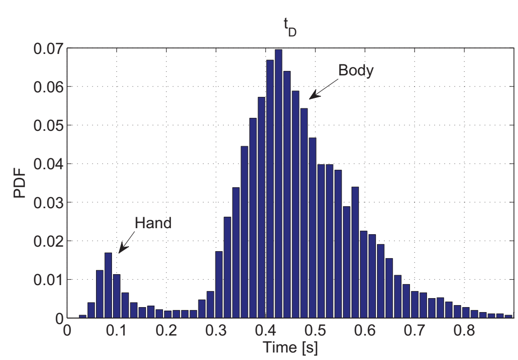
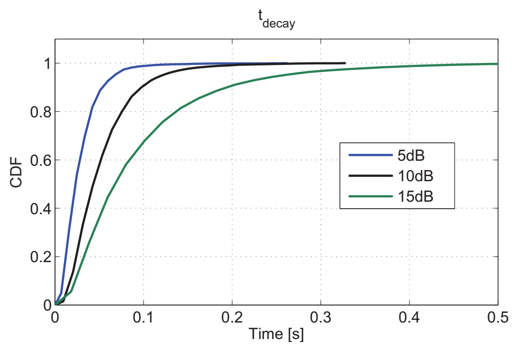
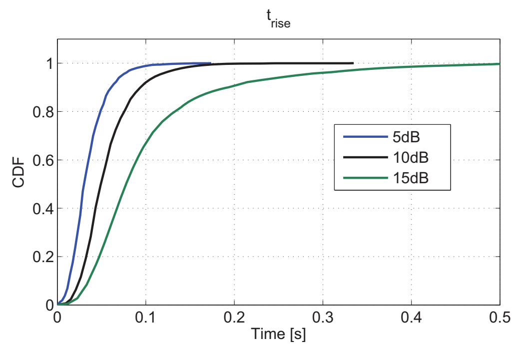


Fig. 4. Probability density function for the parameter t_D in the conference room.



(a) CDF of decay time t_{decay}



(b) CDF of rise time t_{rise}

Fig. 5. Cumulative density functions for the analyzed parameters t_{decay} and t_{rise} in the conference room.

be clearly recognized as two maxima. The duration of the events caused by the swinging motion of the hands amounts to 150 ms in average, however, these events occur much less frequently than those caused by the whole body. With a mean value of 460 ms these events are shorter than in the living room mainly caused by a higher walking speed, but also by the smaller distance between TX and RX and hence a more narrow Fresnel zone.

4) Comparison with literature: In order to proof if the measurement results are reasonable, the temporal parameters can be estimated by knife edge diffraction theory. When a person steps into the zone bound by 0.6 times the radius of the first Fresnel zone, the actual shadowing begins. In case of a distance of 4.38 meters between TX and RX the radius r_1 of the first Fresnel zone equals 7 cm. Assuming a constant walking speed of 0.6 m/s it takes 70 ms until half of the first Fresnel zone is occupied by the person, which leads to a signal drop of 6 dB and hence a slew rate of 85.6 dB/s, which is very close to the observed value in the living room scenario.

III. Modeling

A. Modeling Single Shadowing Events

In order to cover the influence of human-induced channel dynamics in system level simulations that include MAC protocols, both temporal characteristics and signal level/SNR degradation may be considered. Therefore, a statistical model has been developed that is based on the measurement results presented in section II. The dashed curve in Fig. 2a illustrates the modeling approach for a human blockage event. The shadowing event $A(t)$ in dB scale is modeled by a series consisting of a linearly decaying period, a period with a constant signal level A_{mean} and a period with a linearly increasing signal level (dB scale):

$$A(t) = \begin{cases} r_{decay} \cdot t, & \text{for } 0 \leq t \leq \frac{A_{mean}}{r_{decay}} \\ A_{mean}, & \text{for } \frac{A_{mean}}{r_{decay}} \leq t \leq t_D - \frac{A_{mean}}{r_{rise}} \\ A_{mean} - r_{rise} \cdot t, & \text{for } t_D - \frac{A_{mean}}{r_{rise}} \leq t \leq t_D \\ 0, & \text{else} \end{cases} \tag{3}$$

The decay rate r_{decay} as well as the rate of increase r_{rise} can be calculated from the parameters t_{rise} and t_{decay} with Eq. 1 and 2. Approximate probability distributions have been derived for all parameters. Therefore, analytical distributions are compared to the experimental results and validated by the Kolmogorov-Smirnov test with a significance level of 1 % [17]. The tested distribution functions are Gaussian, Weibull and log-normal distribution, whereas the one distribution has been chosen which yielded the clearest Kolmogorov-Smirnov test results. The type of distribution functions and the corresponding model parameters according to [17] are given in Fig. 3a - 3d as well as in Table II. In case of the parameters t_{rise} and t_{decay} the values for a 5 dB threshold have been chosen. All parameters are based on the measurements in the living room scenario.

TABLE II
Model Parameters

Parameter	Distribution	Distribution parameters
$t_D[s]$	Weibull	$\alpha = 0.591, \beta = 6.321$
$A_{mean}[dB]$	Gaussian	$\mu = 13.4, \sigma = 2.0$
$t_{decay,5dB}[s]$	Gaussian	$\mu = 0.061, \sigma = 0.026$
$t_{rise,5dB}[s]$	Log Normal	$\eta = -2.94, \sigma = 0.63)$

B. Application of the model for MAC layer simulations

The IEEE 802.11ad channel model [13] provides space-time characteristics of the 60 GHz propagation channel. To be more precise, the model can be used to generate channel impulse responses including the dependency on azimuth and elevation angles $(\theta_{Rx}, \phi_{Rx}, \theta_{Tx}, \phi_{Tx})$ for both transmit and receive sides. Our model represents the effect of human blockage on a single cluster or the direct path. In system level simulations that include MAC protocols we propose to use the time-variant signal level/SNR degradation in order to account for human activity. Therefore, at first a single angle-dependent channel impulse response $h(\tau, \theta_{Rx}, \phi_{Rx}, \theta_{Tx}, \phi_{Tx})$ is generated by the methods described in the IEEE 802.11ad channel model [13]. Afterwards, chosen clusters are attenuated according to the temporal characteristics of shadowing events (Eq. 3), while other cluster amplitudes remain fixed. We propose to use the probabilities of cluster blockage from Table 3, [13] to choose those clusters who then are attenuated. In order to keep the model complexity low, we propose to use the same temporal characteristics for each of the attenuated clusters. A more accurate approach without this simplification will be investigated in the future. The attenuation of clusters leads to a set of time-correlated impulse responses $h(t, \tau, \theta_{Rx}, \phi_{Rx}, \theta_{Tx}, \phi_{Tx})$. After this, antenna models and beamforming algorithms will be applied to the correlated channel realizations leading to angle-independent impulse responses $h(t, \tau)$. In a final step, the temporal characteristics of the receive signal power level $P(t)$ can be determined, which can then be used in MAC layer simulations. Fig. 6 illustrates the described procedure.

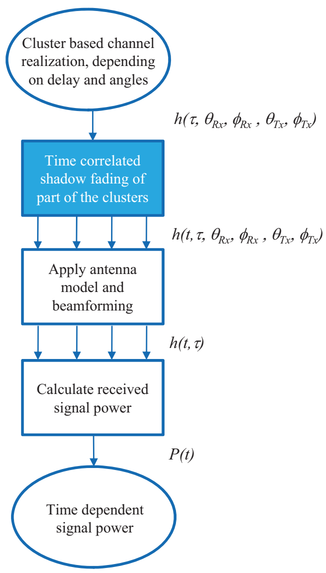


Fig. 6. Flow chart of the procedure for linking the temporal channel characteristics and the 60 GHz channel model for system simulations with MAC protocols.

IV. Conclusion

In this paper, we presented results from a dynamic 60 GHz channel measurement campaign. In addition, a full parameter set for the modeling of human-induced shadow fading events and their application in system simulations with MAC protocols are provided. The investigations have shown that the drop of signal level happens in the order of tens of milliseconds.

In a LOS scenario the 60 GHz signal decreases in average by 20 dB in 230 ms, whereas it takes 16 (61) ms for a drop of 1 (5) dB. The duration of a single fading event amounts to 550 ms in average and the mean attenuation A_{mean} lies between 6 and 18 dB. The investigations have also shown that the shadowing event is not symmetrical and dependent on the walking speed and that even the swinging motion of the human hand can have a significant influence on the radio propagation channel.

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