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Re:	802.15.4a channel modeling
Abstract	Status of channel modeling activities at time of the Portland July 2004) meeting.
Purpose	
Notice	
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Status of models for UWB propagation channels

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***Abstract*—This is a discussion document for the IEEE document of the IEEE 802.15.4a channel modeling subgroup. It gives the current status of the generic channel model for UWB that has been discussed. Feedback from all participants is requested.**

***Index Terms*—UWB, channel model, propagation**

I. Introduction

This document is a summary of the model that the channel-modeling subgroup of IEEE 802.15.4a has (so far) agreed on. The model is intended for a system operating between 2 and 10 GHz; however, the same structure could/should be used for a lower-frequency model as well (mainly for operation between 100 and 960 MHz. While the modeling is done for a ultrawideband system, this is no restriction on the system. Any narrowband model can easily be derived from the UWB model by narrowband filtering.

II. Environments

The following radio environments will be parameterized:

1. Indoor office
2. Indoor residential
3. Indoor industrial
4. Indoor open spaces
5. Warehouses
6. Body devices
7. Out door hand held peer to peer device
8. Hand held communicating to fixed location devices
9. Agricultural areas/farms
10. Sport stadiums
11. Disaster areas (houses filled with rubble, avalanches, ...) ...

III. General Definitions

A. Pathloss

1) Frequency dependence: In a narrowband (in the wireless communications sense) channel, the pathloss is defined as

$$PL = \frac{E\{P_{RX}\}}{P_{TX}} = E\{|H(f_c)|^2\} \tag{1}$$

where P_{TX} and P_{RX} are transmit and receive power, respectively, f_c is the center frequency, and the expectation $E\{\}$ is taken over an area that is large enough to allow averaging out of the shadowing as well as the small-scale fading $E\{\} = E_{lsf}\{E_{ssf}\}\}$. A wideband (in the wireless communications sense) pathloss has been proposed in Ref. [1], [2] as

$$PL = E\{\int |H(f)|^2 df\} \tag{2}$$

where the integration is over the frequency range of interest; it is assumed implicitly that this range is much smaller than the center frequency. In a conventional wireless system, any frequency selectivity of the transfer function stems from the multipath propagation, and is thus related to the small-scale fading. Integration over the frequency and expectation $E_{ssf}\{\}$ thus essentially have the same effect, namely averaging out the small-scale fading.

In a UWB channel, this is not the case anymore. As we have seen in Sec. III, there are frequency-dependent propagation effects. It thus makes sense to define a *frequency-dependent pathloss*

$$PL(f) = E\{\int_{f-\Delta f/2}^{f+\Delta f/2} |H(\widetilde{f})|^2 d\widetilde{f}\} \tag{3}$$

where Δf is chosen small enough so that diffraction coefficients, dielectric constants, etc., can be considered constant within that bandwidth; the $total$ pathloss is obtained by integrating over the whole bandwidth of interest.. It is especially noteworthy that the effective antenna aperture are a function of the frequency. This affects all measurement campaigns that include the antenna as part of the channel.

Two campaigns have measured and modeled the frequency dependency of the pathloss. Ref. [3] found that

$$\sqrt{PL(f)} \propto f^{-m} \tag{4}$$

with m varying between 0.8 and 1.4, while [4] found

$$\log_{10}(PL(f)) \propto \exp(-\delta f) \tag{5}$$

with δ varying between 1 and 1.4.

2) Distance dependence: Naturally, the pathloss also depends on the distance. Pathloss modeling can be simplified by assuming that the frequency dependence and the distance dependence can be treated independently of each other

$$PL(f, d) = PL(f)PL(d). \tag{6}$$

The distance dependence is usually modeled as a power decay law

$$PL(d) = PL(1\text{m}) \left(\frac{d}{1\text{m}}\right)^{-n} \tag{7}$$

where n is the the pathloss exponent. Note that this model is no different from the most common narrowband channel models.

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The many results available in the literature for this case can thus be re-used.

The pathloss exponent also depends on the environment, and on whether a line-of-sight (LOS) connection exists between the transmitter and receiver or not. Some papers even further differentiate between LOS, "soft" NLOS (non-LOS), also known as "obstructed LOS" (OLOS), and "hard NLOS". LOS pathloss exponents in indoor environments range from 1.0 in a corridor [5] to about 2 in an office environment. NLOS exponents typically range from 3 to 4 for soft NLOS, and $4-7$ for hard NLOS. Following the approach of Refs. [6], [7], [8], [9], we suggested to model the pathloss exponent as a random variable that changes from building to building.specifically as a Gaussian distribution. The of the pathloss will be truncated to make sure that only physically reasonable exponents are chosen.

Shadowing, or large-scale fading, is defined as the variation of the local mean around the pathloss. Also this process is fairly similar to the narrowband fading. Again following Ref. [6], we suggest to model the shadowing variance as random variable. The total attenuation due to shadowing and pathloss is

$$[PL_0+10\mu\log(d)]+[10n_1\sigma_\gamma\log_{10}d+n_2\mu_\sigma+n_2n_3\sigma_\sigma] \quad (8)$$

where n_1, n_2 and n_3 are zero-mean, unit-variance Gaussian variables.

B. Delay dispersion, angular dispersion and small-scale fading

1) Arrival statistics of multipath components: We first turn our attention to the power delay profile and the time-of-arrival statistics of the MPCs.

The clustering of MPCs is also reproduced in the Saleh-Valenzuela (SV) model [10], which uses the following discrete-time impulse response:

$$h_{discr}(t)=\sum_{l=0}^{L}\sum_{k=0}^{K}a_{k,l}\delta(t-T_l-\tau_{k,l}), \quad (9)$$

where $a_{k,l}$ is the tap weight of the k^{th} component in the l^{th} cluster, T_l is the delay of the $l-$th cluster, $\tau_{k,l}$ is the delay of the k-th MPC relative to the l-th cluster arrival time T_l. By definition, we have $\tau_{0,l}=0$. The distributions of the cluster arrival times and the ray arrival times are given by a Poisson processes

$$\begin{aligned} p(T_l|T_{l-1}) &= \Lambda_l\exp\left[-\Lambda_l(T_l-T_{l-1})\right],\ l>0 \\ p(\tau_{k,l}|\tau_{(k-1),l} &= \lambda\exp\left[-\lambda(\tau_{k,l}-\tau_{(k-1),l})\right],\ k>0 \end{aligned} \quad (10)$$

where Λ_l is the cluster arrival rate, and λ_l is the ray arrival rate. Note that we have generalized the SV model to account for the (experimentally observed) effect that the cluster arrival rates as well as the path density within each cluster can depend on the delay.

The number of clusters is assumed to be Poisson-distributed, following **??**. The mean number of clusters is a parameter that is different from environment to environment. Also note that the observable number of clusters depends on the delay resolution. When the resolution is poorer than or comparable to the inter-cluster arrival rate, the observable number of clusters decreases.

The intra-cluster arrival rates λ are extracted from the measurements. For those extractions, it is recommended that paths with power that is less than $20dB$ below the peak power are not taken into account.

The power delay profile of each cluster is set to be exponential, though the first arriving path can have higher power than the remainder.

In the SV model, the relative power of each cluster is considered to decay exponentially with rate γ. However, measurements have shown that this is not fulfilled in all environments. Therefore, the relative power of the clusters, as a function of the distance, is an arbitrary parameter that will be determined for each environment separately. No further specifications are done at this point in time.

Furthermore, each cluster undergoes lognormal shadowing that has a constant variance $\sigma_{cluster}$, and that is independent for all clusters. The small-scale fading of the separate clusters

In addition to the discrete paths, there is a superimposed diffuse background radiation

$$h_{diff}(t)=f(t)\zeta \quad (11)$$

where ζ is Rayleigh-distributed random variable. The functional shape of the variance $f(t)$ is not known at this point in time (probably zero at $t=0$, and at very large delays, with a maximum in between). It will have to be extracted from future measurements. The ratio of the power in the discrete components relative to that in the diffuse components is another parameter of the model.

2) Amplitude statistics: The small-scale fading is modeled as Rician or Nakagmai for each delay bin. Both of the two descriptions are admissible (as each has specific advantages in certain contexts). The two distributions are transformed into each other via the relationship

$$m=\frac{(K_\mathrm{r}+1)^2}{(2K_\mathrm{r}+1)} \quad (12)$$

and

$$K_\mathrm{r}=\frac{\sqrt{m^2-m}}{m-\sqrt{m^2-m}}. \quad (13)$$

where K and m are the Rice factor and Nakagami-m factor respectively.

The $m-$factor typically decreases with delay. The exact functional relationship $m(\tau)$ is yet to be determined from measurements (for a low-frequency office environment, [11] give a linear relationship). To simplify the description, the m factor is chosen determistically (in contrast to [11]).

3) Angular dispersion: The different multipath components arrive at the receiver not only with different delays, but also with different angles. This fact is of importance for systems with multiple antennas, as well as for analyzing the impact of nonuniform antenna patterns. In that respect, the angular dispersion does not differ in principle from the widely studied angular dispersion in narrowband systems. The angular power spectrum, i.e., the power (averaged over the small-scale fading) coming from a certain direction, is modeled as a Laplacian function

$$APS(\phi) = \exp(-|\phi - \phi_o|/\sigma_\phi) \tag{14}$$

where the angle ϕ_o of the first arriving cluster is along the (quasi)-LOS, while for the later clusters, it is uniformly distributed between 0 and 2π. Note that the Laplacian distribution needs to be truncated so that $0 < APS < 2\pi$,

The diffuse radiation is usually assumed to be distributed uniformly in angle.

IV. Model structures and parameters

After the general definitions in the previous section, we now give the definitions of the parameters. The frequency range over which the model is valid is $2 - 10.6$ GHz, though it must be stressed that many of the measurements on which the model is based covered only part of this band. The section repeats some aspects of Sec. II, since it is intended as a concise, but comprehensive, summary of the model parameters. Also, it just enumerates the recommended numerical parameters. For details on the measurements they are based on, we refer to the appropriate standards documents.

A. Pathloss

The pathloss as a function of the distance and frequency is given as

$$PL(f,d) = PL(f)PL(d). \tag{15}$$

The distance dependence of the pathloss in dB is described by

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + S + A_{ant} \tag{16}$$

where the reference distance d_0 is set to 1 m. The pathloss at the reference distance is computed according to the free-space pathloss law. n is the pathloss exponent, S is the shadowing, and A_{ant} is the loss of the antenna. Both n and S are normally distributed variables, with means μ_{n} and μ_{S} and variances σ_{n} and σ_{S} respectively. The distribution of n is truncated so that values $n < 1$ are not admissible.

Note also that shadowing has a coherence distance, but due to lack of available measurements, this is not included in the model.

The frequency dependence of the pathloss is given as

$$\sqrt{PL(f)} \propto f^{-\kappa} \tag{17}$$

B. Power delay profile

The impulse response of the SV model is given in general as

$$h_{discr}(t) = \sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}\delta(t - T_l - \tau_{k,l}), \tag{18}$$

where $a_{k,l}$ is the tap weight of the k^{th} component in the l^{th} cluster, T_l is the delay of the $l-$th cluster, $\tau_{k,l}$ is the delay of the k-th MPC relative to the l-th cluster arrival time T_l. The number of clusters L is an important parameter of the model. It is assumed to be Poisson-distributed

$$pdf_L(L) = \frac{(\overline{L})^L \exp(-\overline{L})}{L!} \tag{19}$$

so that the mean $\overline{L}$ completely characterizes the distribution.

By definition, we have $\tau_{0,l} = 0$. The distributions of the cluster arrival times and the ray arrival times are given by a Poisson processes

$$\begin{aligned} p(T_l|T_{l-1}) &= \Lambda_l \exp\left[-\Lambda_l(T_l - T_{l-1})\right],\ l > 0 \\ p(\tau_{k,l}|\tau_{(k-1),l} &= \lambda \exp\left[-\lambda(\tau_{k,l} - \tau_{(k-1),l)})\right],\ k > 0 \end{aligned} \tag{20}$$

where Λ_l is the cluster arrival rate, and λ_l is the ray arrival rate. While a delay dependence of these parameters has been conjectured, no measurements results have been found up to now to support this.

$$E\{|a_{k,l}|^2\} = \Omega_l \exp(-\tau_{k,l}/\gamma_l) \tag{21}$$

where Ω_l is the mean energy of the $l-$th cluster, Γ is the inter-cluster decay time constant, and γ is the intra-cluster decay time constant. The cluster decay rates are found to depend linearly on the arrival time of the cluster,

$$\gamma_l \propto k_\gamma T_l + \gamma_0 \tag{22}$$

The mean (over the cluster shadowing) mean (over the small-scale fading) energy (normalized to γ_l), of the $l-$th cluster follows in general an exponential decay $\exp(-T_l/\Gamma)$, with log-normal variations $\sigma_{cluster}$ around it.

The above parameters give a completel description of the power delay profile. Auxiliary parameters that are helpful in many contexts are the mean excess delay, rms delay spread, and number of multipath components that are within 10 dB of the peak amplitude. Those parameters are used only for informational purposes.

So-called "diffuse" components are not included in the model, due to lack of available measurements.

C. Small-scale fading

The distribution of the small-scale fading is Nakagami

$$pdf(x) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m x^{2m-1}\exp\left(-\frac{m}{\Omega}x^2\right), \tag{23}$$

where *m*≥*1/2* is the Nakagami m-factor, $\Gamma(m)$ is the gamma function, and Ω is the mean-square value of the amplitude. A conversion to a Rice distribution is possible with the conversion equation given above. The parameter Ω corresponds to the mean power, and its delay dependence is thus given by the power delay profile above. The $m-$parameter can have a delay dependence

$$m(\tau) = m_0 - k_{\mathrm{m}}\tau \tag{24}$$

The poarlity (phase) is uniformly distributed.

Directional information and polarization are not included in the model, due to lack of available measurements

D. Complete list of parameters

The considered parameters are thus d_0, μ_{n}, μ_{S}, σ_{n}, σ_{S}, A_{ant}, κ, $\overline{L}$, Λ, λ, Γ, k_γ, γ_0, σ_{cluster}, m_0, k_m.

V. Parameterization in different environments

A. Residential environments [12]

	Residential LOS	NLOS	comments
Pathloss			
d_0	1m	1m	
μ_{n}	1.75	4.49	
σ_{n}	0.35	0.85	
μ_{S}	1.84	3.18	
σ_{S}	0.55	0.94	
A_{ant}	3dB	3dB	
κ	0.72±0.12	0.96±0.3	
Power delay profile			
$\overline{L}$	?	?	
Λ [1/ns]	0.011	0.17	
λ [1/ns]	1.15	2.45	
Γ [ns]	22.33	14.33	
k_γ	0	0	
γ_0 [ns]	5.87	7.17	
σ_{cluster} [dB]	4.02	4.27	
Small-scale fading			
m_0	0.54±0.19	0.73±0.25	
k_m	0	0	

VI. Summary and conclusions

We gave an overview of the generic model for the IEEE 802.15.4a channels. The next important step is to parameterize the other environments.

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