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A REALISTIC RADIO CHANNEL MODEL BASED ON STOCHASTIC PROPAGATION GRAPHS

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The design and optimisation of modern radio communication systems require realistic models of the radio propagation channel, which incorporate dispersion in delay, Doppler frequency, direction of departure, direction of arrival, and polarisation. Often radio communication systems are assessed by Monte Carlo simulations in which stochastic models are used to generate synthetic realisations of the response of the radio channel.

Traditional stochastic radio channel models reflect the statistical properties of the (time-variant or time-invariant) impulse response of the channel between the input of any antenna element at the transmitter site and any antenna element at the receiver site. The probability distributions of the parameters of the channel impulse response are generally difficult to obtain from environment parameters such as the scatterer size and density. Instead, the model parameters are often inferred from measurements. Motivated by experimental results conventional models implement an exponentially decaying power-delay-profile by including various ad-hoc constraints on the random model parameters. These approaches, however, do not reflect the underlying physical mechanisms that lead to this decaying behaviour.

In this contribution we present a stochastic model of the radio propagation environment based on a random propagation graph. A propagation graph is defined by a set of vertices (the transmitter, the receiver and the scatterers) and a set of edges (visibility between scatterers). The position of the scatterers and the edges of a propagation graph are drawn randomly according to some probability density functions.

The propagation process is modelled as follows. The transmitter vertex emits an electromagnetic signal illuminating a subset of the vertices. As a signal propagates along an edge of the propagation graph, it is delayed and attenuated depending on the length of the edge. When the signal arrives at a scatterer it is re-radiated by the scatterer. The interaction between the signal and a scatterer is modelled as a scatter-gain weighting all signals arriving at this scatterer. From a realisation of the propagation graph the received signal of a specific communication system can be computed.

Simulations show that under the assumption of an inverse squared distance power decay, the proposed model yields the often observed exponentially decaying power-delay-profile. This effect stems from the structure of the propagation graph and is not obtained by introducing any artificial constraints. The channel realisations obtained from the model also exhibit a transition from specular contributions for small delays to a diffuse part at long delays with a mixture of specular and diffuse contributions at intermediate delays. This feature is also observed experimentally, especially in investigations for ultra wide band systems. The model for the power-delay-profile can be easily extended to include dispersion in direction of departure and direction of arrival.

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Abstract. In this contribution a propagation model is derived based on the so-called propagation graph. It is shown by means of Monte Carlo simulations that the obtained model as a result of its inherent structure predicts an exponentially decaying power-delay-profile as commonly reported from measurements. Furthermore, the power-delay-profile obtained with the proposed model exhibit a transition from specular components at small delays to diffuse components at long delays. This feature was also observed, especially in experimental investigations for ultra wide band systems.

1. Introduction

The design and optimisation of modern radio communication systems require realistic models of the radio propagation channel, which incorporate dispersion in delay, Doppler frequency, direction of departure, direction of arrival, and polarisation. Often radio communication systems are assessed by Monte Carlo simulations in which stochastic models are used to generate synthetic realisations of the response of the radio propagation channel.

Traditional stochastic radio channel models reflect the statistical properties of the (time-variant or time-invariant) impulse response of the channel between the input of any antenna element at the transmitter site and any antenna element at the receiver site. The probability distributions of the parameters of the channel impulse response are generally difficult to obtain from environment parameters such as the scatterer size and density. Instead, the model parameters are often inferred from measurements. Motivated by experimental results conventional models implement an exponentially decaying power-delay-profile by including various ad-hoc constraints on the random model parameters. The two contributions [1] and [2] follow this approach. In these models a key parameter for modelling the arrival times of individual signal components is the “cluster arrival rate”. However this parameter is difficult to derive from a propagation environment. In the model given in [3] the scattering coefficients are corrected to obtain the effects observed from measurements like the exponential decay of the power-delay-profile. These approaches, however, do not reflect the underlying physical mechanisms that lead to this decaying behaviour.

A different approach is followed Franceschetti in [4] where the radio propagation mechanism is modelled as a “stream of photons” performing a continuous random walk in a cluttered environment with constant clutter density. The transmitted signal is a pulse of finite duration. When a photon interacts with an obstacle, it is either absorbed (with a certain probability) or scattered and changes direction. The Franceschetti model is mainly a descriptive model for the delay power spectrum; it is not possible to obtain realisations of the channel impulse responses from this model. Furthermore,

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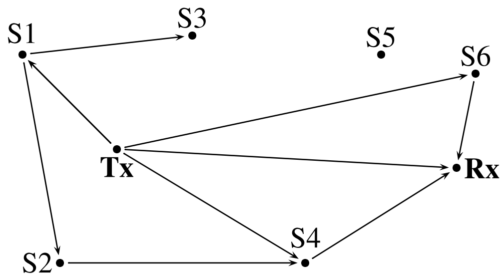

Fig. 1. One realisation of a propagation graph with six scatterers.

the model does not cover the transition from specular to diffuse signal contributions as observed in [5].

In this contribution we present a stochastic model of the radio-propagation environment based on a random propagation graph. The model can incorporate dispersion in delay, (bi)-directions, Doppler frequency, *etc*. The aim is to obtain a stochastic model that leads to realisations of the channel response with features similar to those observed in measured responses.

The remaining part of the paper is organised as follows. Section 2 reviews the needed fundamentals of directed graphs. In Section 3 the stochastic propagation graph is described. Using this model, we give an example of the resulting power-delay-profile in Section 4. Concluding remarks are adressed in Section 5.

2. Directed Graphs

Following [6] we define a directed graph $\mathcal{G}$ as a pair $(\mathcal{V}, \mathcal{E})$ of disjoint sets (of vertices and edges) together with the two mappings $\mathrm{init} : \mathcal{E} \to \mathcal{V}$ and $\mathrm{term} : \mathcal{E} \to \mathcal{V}$ assigning every edge $e \in \mathcal{E}$ an initial vertex $\mathrm{init}(e)$ and a terminal point $\mathrm{term}(e)$. An edge $e \in \mathcal{E}$ that fulfils $\mathrm{init}(e) = \mathrm{term}(e)$ is called a loop. Two edges e and e' are parallel if $\mathrm{init}(e) = \mathrm{init}(e')$ and $\mathrm{term}(e) = \mathrm{term}(e')$. A walk (of length K) in a graph $\mathcal{G}$ is a non-empty alternating sequence $\langle v_1, e_1, v_2, e_2, \ldots, e_K, v_{K+1}\rangle$ of vertices and edges in $\mathcal{G}$ such that $\mathrm{init}(e_k) = v_k$ and $\mathrm{term}(e_k) = v_{k+1}$, $1 \leq k < K$. A path is a walk, with no parallel edges and where the vertices $v_2, \ldots, v_{K-1}$ are distinct. If a path that fulfils $v_1 = v_K$, is called cycle.

3. Propagation graphs

A propagation graph is a special case of a directed graph. An example of a propagation graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with $\mathcal{V} = \{\mathrm{Tx}, \mathrm{Rx}, \mathrm{S1}, \ldots, \mathrm{S6}\}$ is shown in Fig. 1. The vertices of a propagation graph model the transmitter (Tx), the receiver (Rx) and the scatterers (S1,...,S6). The edges model the visibility between vertices meaning that a signal emitted from the initial vertex is received delayed and attenuated at the terminal vertex. In the depicted case, the signal emitted from the Tx vertex is observed by the Rx, S1, S4 and S6 vertices, whereas a signal emitted from S3 or S5 is not observable from any vertex. We restrict the discussion to propagation graphs with no loops nor parallel edges. In this case we may identify the edge e with $(\mathrm{init}(e), \mathrm{term}(e)) \in \mathcal{V}^2$ and write $e = (\mathrm{init}(e), \mathrm{term}(e))$ with a slight abuse of notation. With this identification, $\mathcal{E} \subseteq \mathcal{V}^2$. If we consider two vertices $v_1, v_2 \in \mathcal{V}$ then $e = (v_1, v_2) \in \mathcal{E}$ is fulfilled with probability P_e. As the propagation graphs contain no loops, $P_{(v,v)} = 0$. The Tx is a source, and hence there exists no edge with Tx as terminal point, that is $P_{(v,\mathrm{Tx})} = 0$. Likewise, the Rx vertex is considered a sink and therefore $P_{(\mathrm{Rx},v)} = 0$.

The spatial positions of a vertex (a scatterer) $v \in \mathcal{V}$ with respect to some arbitrary origin is given by a spatial displacement $\vec{r}_v \in \mathcal{R} \subseteq \mathbb{R}^3$, where $\mathbb{R}$ denotes the real line and $\mathcal{R}$ is the region in which the scatterers that significantly affect the propagation mechanisms between the Tx and Rx are located. The propagation time of the signal propagating along edge $e = (v_1, v_2)$ can be calculated as

$$\Delta\tau_e = |\vec{r}_{v_1} - \vec{r}_{v_2}| \cdot c^{-1}, \tag{1}$$

where $c \approx 3 \cdot 10^8 \, \frac{\mathrm{m}}{\mathrm{s}}$ is the speed of light (in air) and $|\cdot|$ denotes the Euclidian norm.

We model a wave interaction with a scatterer v as a scatter-gain g_v weighting all signals arriving at v. The gain can be complex if we work in complex base-band notation (e.g. of narrow-band and wide-band signals) or a real number if we describe the signals directly (e.g. for ultra-wide-band signals). In both cases, we restrict the magnitude of g_v as $|g_v| < 1$. In this contribution we assume that $g_v = g$ for all v, where g is a known constant. In general g_v might be modelled as a random variable. We assume an inverse squared distance power law. Therefore the gain of the signal being scattered by $\mathrm{init}(e)$ observed at $\mathrm{term}(e)$ is given by

$$a_e = g \cdot \Delta\tau_e^{-2}. \tag{2}$$

Note that g is not dimensionless; it is given in $[\mathrm{s}^2]$. Thus, a_e is dimensionless.

A propagation path $\mathcal{G}$ is defined as a walk $\ell = \langle v_1, e_1, v_2, e_2, \ldots, e_{K_\ell}, v_{K_\ell+1}\rangle$ in $\mathcal{G}$ that fulfils $v_1 = \mathrm{Tx}$ and $v_{K_\ell+1} = \mathrm{Rx}$. The propagation path $\langle \mathrm{Tx}, (\mathrm{Tx}, \mathrm{Rx}), \mathrm{Rx}\rangle$ is called the line-of-sight path provided it exists. The set of all propagation paths in $\mathcal{G}$ is denoted by $\mathcal{L}(\mathcal{G})$. The signal received at the Rx is a superposition of all signal components each propagating via a propagation path $\ell \in \mathcal{L}(\mathcal{G})$. The number of signal components in the received signal therefore equals the cardinality of $\mathcal{L}(\mathcal{G})$. This number can be finite as in the case depicted in Fig. 1 or infinite if there exists at least one path connecting Tx and Rx with a cycle.

The delay τ_ℓ and gain α_ℓ of a propagation path $\ell \in \mathcal{L}(\mathcal{G})$ can be calculated by repetitively using (1) and (2) as

$$\alpha_\ell = \prod_{k=1}^{K_\ell} a_{e_k} \quad \text{and} \quad \tau_\ell = \sum_{k=1}^{K_\ell} \Delta\tau_{e_k} \tag{3}$$

Hence, the impulse response $h_\mathcal{G}(\tau)$ of the propagation graph can be obtained as

$$h_\mathcal{G}(\tau) = \sum_{\ell \in \mathcal{L}(\mathcal{G})} h_\ell(\tau) \tag{4}$$

with $h_\ell(\tau) = \alpha_\ell \delta(\tau - \tau_\ell)$, where $\delta(\cdot)$ is the Dirac unit impulse.

4. Simulation Study

In the sequel we investigate the power-delay-profile of the propagation graph model by means of a Monte-Carlo simulation. In this simulation the following scenario is assumed:

1) A constant number N of scatterers is assumed.
2) The region $\mathcal{R}$ is assumed to be a rectangular solid box.
3) The positions of the N scatterers $\mathrm{S}1, \ldots, \mathrm{S}N$ are drawn according to a uniform distribution defined on $\mathcal{R}$.
4) The Tx and Rx have fixed coordinates, i.e. $\vec{r}_{\mathrm{Tx}}, \vec{r}_{\mathrm{Rx}} \in \mathcal{R}$ and are known vectors.

TABLE I

PARAMETER SETTING FOR THE SIMULATION

Parameters	Values
$\mathcal{R}$	$[0,2]\times[0,3]\times[0,5]\,\mathrm{m}^3$
$\vec{r}_{Tx}$	$[1.8, 2.0, 0.5]^{\mathrm{T}}$ m
$\vec{r}_{Rx}$	$[1.0, 1.0, 4.0]^{\mathrm{T}}$ m
N	50
g	0.1 s^2
P_{vis}	0.08
Number of Monte Carlo runs	100

5) We define P_e as

$$P_e = \begin{cases} 1 & \text{if } e = (\mathrm{Tx}, \mathrm{Rx}), \\ P_{\text{vis}} & \text{if } e = (v_1, v_2), \text{ where } v_1 \in \mathcal{V}\backslash\{\mathrm{Tx}\}, v_2 \in \mathcal{V}\backslash\{\mathrm{Rx}\}, \text{ and} \\ 0 & \text{otherwise.} \end{cases}$$

The settings are given in Table I. The region $\mathcal{R}$ has a volume of $30\,\mathrm{m}^3$ which yield an scatter density of roughly $1.7\,\mathrm{m}^{-3}$. In each Monte Carlo run, the propagation graph is generated randomly and the resulting τ_ℓ's and α_ℓ's are computed.

The (averaged) power-delay-profile $\mathrm{E}_{\mathcal{G}}[|h_{\mathcal{G}}(\tau)|^2]$ (assuming a small, but finite observation bandwidth) is reported together with three individual channel realisations in Fig. 2. It appears from the figure that the proposed model exhibits an exponentially decaying power-delay-profile. Since we assumed an inverse squared distance power law, the exponential power decay stems from the structure of the propagation model alone. The individual channel realisations are depicted as a scatter plot of the $(\tau_\ell, |\alpha_\ell|^2)$'s obtained for each channel realisation. The reported individual channel realisations all exhibit the same behaviour: for $\tau < \Delta\tau_{(\mathrm{Tx},\mathrm{Rx})} = |\vec{r}_{Tx} - \vec{r}_{Rx}| \cdot c^{-1} \approx 12.4$ ns, the channel impulse response is zero; for $\tau \geq \Delta\tau_{(\mathrm{Tx},\mathrm{Rx})}$ the "occurrence rate" of the signal contribution increases with the delay. As a result the impulse response consists of a specular short-delay part (including the line-of-sight path) and a diffuse tail part for large delay with a transitional mix of specular and diffuse components in the intermediate delay range. This transition effect is observed from measurements in [5]. The behaviour is expected since for a longer delay the signal is spread through the propagation graph and an increasing number of components exist.

5. Conclusions

A propagation model based on a stochastic propagation graph was proposed. A propagation graph is defined by a set of vertices (scatterers) and a set of edges (visibility between scatterers). These parameters can be drawn randomly according to some probability density function. Based on measurement results conventional models implement an exponentially decaying power-delay-profile by various assumptions. These approaches, however, do not reflect the underlying physical mechanisms that lead to this decaying behaviour. It was shown by simulation that assuming an inverse squared distance power decay, the proposed model yields the often observed exponentially decaying power-delay-profile. This effect stems from the structure of the propagation graph and is not obtained by introducing any artificial assumptions. The channel realisations obtained from the model also exhibit a transition from specular contributions for low delays to a diffuse part at long delays as observed in measurements. The model can be easily extended to include dispersion in directions of departure and arrival.

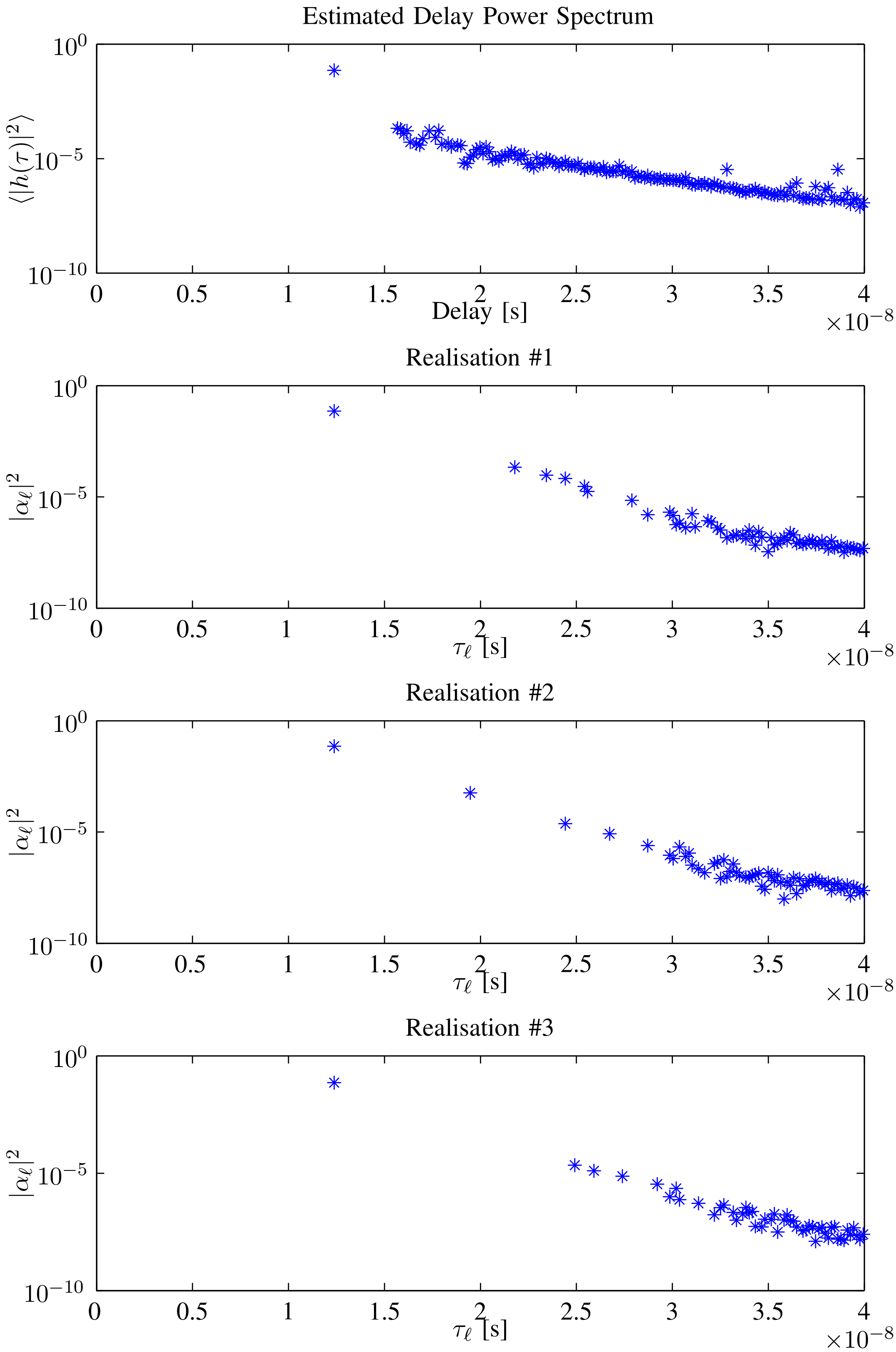

Fig. 2. Estimated delay power spectrum and three individual realisations of the channel impulse response. The parameter setting is given in Table I.

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