On Propagation Graph Model for Industrial UWB Channels

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***Abstract*—This paper investigates the suitability of a propagation graph (PG) model for ultra wideband (UWB) industrial wireless channels. Based on short range UWB channel sounding measurements in typical industrial scenarios, we estimate parameters of the model using a method of moments. The measurements are then compared with approximate expressions for the power delay profile derived based on PG formalism. Results show reasonable agreement between the measured and simulated UWB channel response from the model.**

***Index Terms*—Propagation graph, industrial channel, UWB, wireless channels**

I. Introduction

Propagation graphs (PGs) offer a flexible structure for modelling reverberant propagation with account for infinite scattering [1]. Within the last few years, the PG model have attracted significant research interest resulting in its application to different propagation scenarios including: millimetre wave [2], high speed railway, indoor to outdoor, multi-room [3] and polarized [4] channel. Hybrid models combining the PG with other modelling frameworks have also been studied.

The growing interest in the propagation graph model may not be unconnected to its relative benefits compared to classical modelling approaches such as ray-tracing and geometry based spatial channel model. These benefits include analytical computation of the channel transfer function based on the physics of electromagnetic wave propagation, low computational complexity, easy generalization to multi-user scenarios and applicability over different frequency bands [4].

Models for industrial propagation are crucial to the design and performance evaluation of communication systems as an enabler for the current industrial revolution, i.e., Industry 4.0. In this paper, we present the first study on propagation graph modeling for industrial channels as well as ultra-wideband (UWB) communication.

II. Model, Measurement and Parameter Estimation

A. Propagation Graph Model

In this section, we introduce the propagation graph based model presented in [1]. We consider a simple directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with vertex set $\mathcal{V} = \mathcal{V}_{\rm t} \cup \mathcal{V}_{\rm s} \cup \mathcal{V}_{\rm r}$ which is a union of three disjoint sets: a set of transmitters, $\mathcal{V}_{\rm t}$, a set of scatterers, $\mathcal{V}_{\rm s}$ and a set of receivers, $\mathcal{V}_{\rm r}$. Wave propagation between the vertices is modelled by edges in $\mathcal{E}$. An edge, $e = (v, w)$, exists if and only if a wave can propagate directly from v to w.

Wave propagation in the graph is defined by the actions of the scatterers and edges. A scatterer re-emits weighted version of the sum of signals arriving via the incoming edges to the outgoing edges. An edge $(v, w) \in \mathcal{E}$ transfers a signal from v to w according to its transfer function, $A_{(v,w)}$. We set $A_e(f) = 0$ for $e \notin \mathcal{E}$. The edge transfer functions are collected into sub-matrices: $\mathbf{D}(f)$: transmitters $\rightarrow$ receivers, $\mathbf{T}(f)$: transmitters $\rightarrow$ scatterers, $\mathbf{R}(f)$: scatterers $\rightarrow$ receivers, $\mathbf{B}(f)$: scatterers $\rightarrow$ scatterers.

Assuming that the channel is time-invariant, the transfer matrix, $\mathbf{H}(f)$ of the propagation graph can be expressed in closed form as [1]

$$\mathbf{H}(f) = \mathbf{D}(f) + \mathbf{R}(f)[\mathbf{I} - \mathbf{B}(f)]^{-1}\mathbf{T}(f), \tag{1}$$

provided that the spectral radius of $\mathbf{B}(f)$ is less than unity. As in [5], the edge transfer functions are defined as

$$A_e(f) = \begin{cases} g_e(f)\exp(j2\pi f\tau_e + \phi_e); & e \in \mathcal{E} \\ 0; & e \notin \mathcal{E}, \end{cases} \tag{2}$$

with where τ_e is the edge delay, ϕ_e is the random initial phase of and $g_e(f)$ denotes the edge gain which can be calculated from [1]

$$g_e(f) = \begin{cases} \frac{G_{\rm r}G_{\rm t}}{(4\pi f\tau_e)}; & e \in \mathcal{E}_{\rm d} \\ \frac{G_{\rm t}}{\sqrt{4\pi\tau_e^2 f\mu(\mathcal{E}_{\rm t})\mathcal{S}(\mathcal{E}_{\rm t})}}; & e \in \mathcal{E}_{\rm t} \\ \frac{g}{\mathrm{odi}(e)}; & e \in \mathcal{E}_{\rm s} \\ \frac{G_{\rm t}}{\sqrt{4\pi\tau_e^2 f\mu(\mathcal{E}_{\rm r})\mathcal{S}(\mathcal{E}_{\rm r})}}; & e \in \mathcal{E}_{\rm r}, \end{cases} \tag{3}$$

Here, g denotes the reflection gain, $\mathrm{odi}(e)$ denotes the number of outgoing edges from the nth scatterer,

$$\mu(\mathcal{E}_{\rm a}) = \frac{1}{|\mathcal{E}_{\rm a}|}\sum_{e\subset\mathcal{E}_{\rm a}}\tau_e, \quad \mathcal{S}(\mathcal{E}_{\rm a}) = \sum_{e\subset\mathcal{E}_{\rm a}}\tau_e^{-2}, \quad \mathcal{E}_{\rm a} \subset \mathcal{E}, \tag{4}$$

where $|\cdot|$ denotes set cardinality. A method for stochastically generating transfer function and impulse response from the PG is presented in [1].

B. Method of Moment

As in [4], [6], we approximate the full propagation graph by the simple graph shown in Fig. 1. On average, each edge in the PG is connected to $P_{\rm vis}(N_{\rm s} - 1)$ vertices, i.e., $\mathbb{E}[|\mathcal{E}_{\rm a}|] = P_{\rm vis}(N_{\rm s} - 1)$, where $P_{\rm vis}$ and $N_{\rm s}$ are the probability of visibility and number of scatterers, respectively. Using (3) and Fig. 1, the power delay spectrum (PDS) for the non-polarized graph can be obtained following [4], [6] as

$$P(\tau) = \frac{g^{(2\tau/\mu_\tau)}}{P_{\rm vis}(N_{\rm s} - 1)(4\pi\mu_\tau)^2} \tag{5}$$

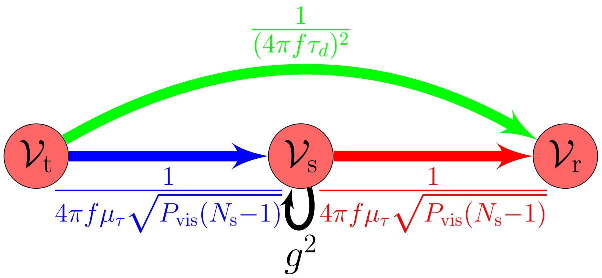

Fig. 1: Simplified model for the power transfer in a non-polarized graph.

TABLE I: Estimated Model Parameters.

Measurement	**Room Size**	**Model Parameters**	
		g	$N_{\rm s}$
LCD	$41 \times 14 \times 6\,{\rm m}^3$	0.73	9
HCD	$33 \times 14 \times 6\,{\rm m}^3$	0.67	60

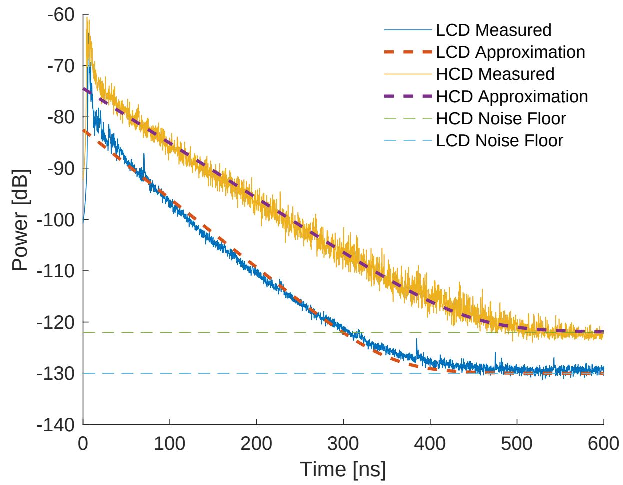

Fig. 2: Measured averaged power delay profile and approximate expression for the two industrial environments.

where μ_τ is the mean path delay defined in terms of the room volume, V and total surface area, S as $\mu_\tau = 4V/cS$, where c is the speed of light. The method of moment (MoM) [4] estimates the model parameters g and the effective number of scaterrers $P_{vis}N_{\rm s}$ via a non-linear least square fit of the empirical power delay profile to the PDS in (5).

C. Measurements

The measurement data are from a recent short-range UWB measurement campaigns conducted in a $33 \times 14 \times 6$ m^3 high cluster density (HCD) and a $41 \times 14 \times 6$ m^3 low cluter density (LCD) environment at the Smart Production Lab, Aalborg University (AAU), Denmark. The HCD was a factory hall with large metallic machinery including hydraulic press, welding machines, and material processing machines. On the other hand, the LCD contained robots, laboratory machinery, and a production line, surrounded by large empty areas. In both cases, measurements were collected using a Rhode & Schwarz ZND 8.5 GHz VNA with omnidirectional broadband biconical antennas at the transceivers over a 5 GHz bandwidth from 3 GHz to 8 GHz. During the campaigns, the transmitter's location was fixed while that of the receiver was varied between 1 m and 9 m horizontal distances. A total of 95 and 98 channel transfer functions were obtained for the HCD and LCD, respectively. Measurements were performed with a resolution of 1 MHz corresponding to a total of 5001 samples over the entire bandwidth. Further description of the measurements can be found in [7].

III. Simulation and Results

As in [4], we set the probability of visibility, $P_{\rm vis} = 0.9$ and estimate the reflection gain, g and number of scatterers, $N_{\rm s}$ for each environment using the MoM described in Section II. The estimated parameters for both environments are shown in Table I. As expected, $N_{\rm s}$ is much larger for the factory hall with high cluster density. In contrast, a lower reflection gain is obtained for the low clutter environment indicating a faster decay of the PDP with low number of scatterers.

In Fig. 2, we show the approximate PDS obtained using (5) with the estimated parameters and the measured PDS. The figures show a very good fit between the approximate PDS and the empirical PDP from both measurements indicating the suitability of the PG for industrial UWB channels.

IV. Conclusion

An investigation on the suitability of a propagation graph model for characterizing short-range industrial UWB channels is presented in this paper. An approximate expression for the power delay spectrum based on propagation graph formalism is used to estimate the model parameters via a method of moment. Results showed a good match between the measured PDP and the PG approximation.

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