D6.1.7: Propagation Models for Smart Grids Communications

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Abstract

This report concentrates on elaboration of the radio communications signal propagation and path loss models suitable for smart grids. The radio propagation models concentrate on LTE technology and suitable channel models for it.

The contents of the reports are mainly intended for providing input to the upcoming deliverable D6.1.8: Traffic requirements and dimensioning for smart grids communications, which concentrates on simulations in a suburban smart metering scenario. The information presented here is given on a more generic level where the reader can be easily directed to more specific contents regarding various channel modelling aspects in smart grids.

The report firstly gives a short introduction to the topic. Secondly, various aspects of radio channel modelling are discussed followed by a more in depth description of outdoor, indoor and outdoor-to-indoor propagation.

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1 Preface

This report was done as a part of the Finnish national research project "Smart Grid and Energy Market" SGEM.

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I would also like to thank our partners from NSN in providing valuable assistance in scoping our scenario.

2 Scope

This report describes different ways of modelling outdoor, indoor, and outdoor-to-indoor propagation of radio signals. The propagation aspects concentrate on Smart Grids and LTE technology. The contents are rather a literature survey of existing models and serve as input for more detailed simulations for a particular scenario.

3 Introduction

3.1.1 Propagation scenarios

The physical environments of Smart Grid (SG) nodes are rural, suburban and urban locations. It is assumed that SG devices or nodes are located in *fixed positions*, and therefore the time variations of the radio channel properties are minimal or very slow. Signal penetration into buildings cause *entry loss* that needs to be taken into account in the link budget. Three propagation link types are assumed; *outdoor*, *indoor* and *indoor-to-outdoor*. The communication system is using LTE approach, i.e. multiple antennas are being used in transmitter and receiver ends (MIMO channel).

3.1.2 LTE channel model

LTE uses Orthogonal Frequency Division Multiplexing (OFDM) technique to combat multipath propagation. Frequency-variable channel appears flat over the narrow band of an OFDM subcarrier, i.e. the frequency-and time-variable fading channel is transformed into parallel correlated flat-fading channels, eliminating the need for complex equalization. Thus narrowband channel models can be applied to estimate the LTE channel. LTE uses MIMO concept with 2x2, 2x4 or 4x4 antenna configurations. MIMO approach tries to achieve capacity gain through utilisation of independent, identically distributed fading channels between the TX-RX antennas. The i.i.d. assumption is not necessarily true in real life, so the MIMO channel correlation needs to be addressed in the models.

4 Radio Channel Modelling

4.1.1 Basics of Modelling a Radio Channel

The radio signal propagates through a *multipath channel*. Reflections from multiple scatterers located at different distances cause the echoes of the signal to arrive at different time instances with respect to the line-of-sight (LOS) signal. At the receiver, these signal components are superimposed over the delay axis. In a static, non-mobile situation, the radio channel parameters describing the channel state are constant. In a mobile case the environment is constantly changing, and the channel parameters are time-variant. This variation over time causes the multipath propagated radio signal to follow a random *fading process*.

4.1.1.1 Narrowband Modelling

Narrowband modelling of the fading outdoor radio channel does not concern the delay domain of the received signal. All signal components are summed together to a single time-variant signal. Path loss models have been developed to estimate the average signal level at the receiver. Adding a fade margin into link budget calculations mitigates the effect of fading.

Narrowband models have different approaches. Empirical models are channel measurements without physical explanation of propagation mechanisms. Semi-deterministic (physical-empirical) models are empirical models that try to explain the propagation mechanisms by diffraction and reflection. Statistical models are developed for propagation in mobile (sub)urban and rural environments. [Sau07] describes these models in detail.

4.1.1.2 Empirical Narrowband Models

Commonly known narrowband macro-cell models are the power-law model (rural), Egli's clutter factor model (rural); based on a plane earth model with a clutter factor, the Okumura-Hata (empirical model, urban, suburban), and frequency extended COST231-Hata model (Urban, suburban). Lee's model is a simple propagation model for mobile environments whereas the Ibrahim-Parsons model is a more sophisticated urban mobile channel model.

4.1.1.3 Deterministic Narrowband Models

Allsebrook-Parsons model is a plane earth model plus a knife-edge diffraction at the final obstacle. Ikegami adds a single reflection into Allsebrook-Parsons. Rooftop diffraction model uses multiple knife-edge diffractions. Flat-edge diffraction model is a simplified rooftop model with all obstacles having the same height. The Walfish-Bertoni model assumes multiple building diffractions. Finally, COST231-Walfish/Ikegami model uses Walfish-Bertoni model for building diffraction and then uses Ikegami model for the final building diffraction.

4.1.1.4 Wideband Modelling

In wideband modelling of the ***time-variant multipath channel***, the delay axis is split into narrow bins and all signal components falling into the same bin contribute to a single propagation path. The received signal is a sum of these delayed paths. This approach is analogous to filtering a signal using a FIR filter whose *tap coefficients* are time-variant. Being a sum of time-variant signal components, the amplitude and phase of the received signal changes over time.

The *delay spread* of the received fading signal, τ_{RMS}, describes the concentration of the signal energy around its mean delay value. *Coherence bandwidth, B_c,* is inversely related to the delay spread as $B_c = 2\pi/\tau_{RMS}$. The coherence bandwidth measures the separation in frequency after which two signals will experience uncorrelated fading. If all frequencies of the signal are within the coherence bandwidth, they all face the same propagation conditions and fade at the same time of instant. Hence the radio channel is called *flat fading channel*. In *frequency-selective fading*, the coherence bandwidth of the channel is smaller than the bandwidth of the signal, and different frequency components of the signal experience de-correlated fading.

Since each filter tap contains a number of super-imposed paths with independent fading processes, their amplitudes follow a Rayleigh distribution. If there is a dominant signal component in the tap, as most often is the case in *pure line of sight* (LoS) situation, the tap amplitude is Ricean distributed. The Rice K-factor is used as a merit between specular (Ricean) and diffuse (Rayleigh) scattering. In an *obscured LOS* situation the dominant signal component is attenuated and the LOS component (i.e. the tap with zero delay), and the tap amplitude distribution has a lower K-factor. Note accordingly that in a case of a specular reflection, a delayed path can follow a Ricean distribution with a high K-factor, although this a special case.

In a mobile environment, not only the transmitter-receiver link is chancing but also the scatterers causing the multipath propagation are moving at different speeds with respect to the transmitter and receiver. Since the path delays, and hence the phases, are varying there will Doppler shifts present in the received signal components. The difference in Doppler shifts between different signal components contributing to a single fading channel tap is known as the *Doppler spread*. Modelling the time-variance of the radio channel, the filter taps are assumed to have a so-called *classical spectrum*, whose width is the Doppler spread.

Channels with a large Doppler spread have signal components that are each changing independently in phase over time. Since fading depends on whether signal components add constructively or destructively, such radio channels have a very short coherence time. In general, coherence time, T_c, is inversely related to Doppler spread as $T_c \sim 1/D_D$.

Slow fading (shadowing) arises when the coherence time of the channel is large relative to the delay constraint of the channel. In this regime, the amplitude and phase change imposed by the channel can be considered roughly constant over the period of use. Slow fading can be caused by events, such as, shadowing, where a large obstruction, e.g. a hill or large building obscures the main signal path between the transmitter and the receiver. The amplitude change caused by shadowing is often modelled using log-normal distribution with a standard deviation according to the log-distance path loss model.

Fast fading occurs when the coherence time of the channel is small relative to the delay constraint of the channel. In this regime, the amplitude and phase change imposed by the channel varies considerably over the period of use.

4.1.1.5 Spatial Channel Modelling (MIMO)

In contrast to conventional communication systems with one transmit and one receive antenna, MIMO systems are equipped with multiple antennas at both link ends. As a consequence, the MIMO channel has to be described for all transmit and receive antenna pairs. From a system level perspective, a linear time-variant MIMO channel is then represented by an n × m channel matrix.

The Winner Spatial Channel Model (SCM) and its extension SCME take into account not only the delay spread, but also the angle spread of the received signal.

4.1.2 Outdoor Radio Propagation

Narrowband outdoor models are listed above, and are discussed in detail in [Sau07]. These models can readily be applied into LTE systems, when the OFDM subcarriers are assumed to be flat-fading. In modelling the LTE channel for fixed SG devices, it is sufficient to consider OFDM symbols only in frequency-domain, since the time variance of the channel is assumed to be negligible. When there is significant time-variance present in the channel, the reference symbols are scattered in time and frequency domains, and it is necessary to consider the channel in two dimensions simultaneously.

4.1.3 Indoor and Outdoor-to-Indoor propagation

Estimation of the outdoor to indoor propagation effects is more complicated due to more complicated radio environment. By excluding the exterior wall penetration, outdoor-to-indoor propagation environment is reduced into an indoor propagation situation.

Building entry loss (penetration loss) is discussed in [Fon09] Ch 1, tabulating the electrical properties of various building materials. According to the magnitude of the penetration loss, hard partitions and soft partitions can be distinguished and tabulated [Rap91],[Rap96]. Besides the attenuation due to internal walls and floors, attenuation due to an external wall is one of the effects contributing to the overall attenuation of the received signal. [And04] gives partition attenuation for several types of materials at 2.5 GHz and 60 GHz. In [Zha94a] penetration loss of various types of concrete and plasterboard walls in the frequency range of 900 MHz to 18 GHz are presented.

Signal attenuation due to external wall, besides internal walls attenuation and floor attenuation, is one of the effects contributing to the overall attenuation of the received signal. A detailed survey on indoor propagation, both narrowband and wideband is available in [Mol91].

In general, attenuation of signal received inside building decreases with height. The rate of change of penetration loss with height (height factor) for both cases of propagation into building and propagation within building for 900 MHz, 1800 MHz and 2300 MHz is given in [Tol98]. The measurements presented here also show decrease of penetration loss with frequency (at 900 MHz, 1800 MHz and 2300 MHz). The transmitter was in all cases placed on the roof of a neighbouring building. Measurement results of building penetration loss at 1800 MHz together with height factor are presented in [Mar03]. [Hor86] demonstrates the influence of the incidence angle on the penetration loss at 1.2 GHz and states that the dependence of the penetration loss on the incidence angle is almost linear.

In [Sil03], a statistical model (distribution throughout a room) for a so-called window gain is provided. Various approaches can be applied when modelling propagation through windows. These approaches include finite-difference time domain (FDTD), parabolic equation [Noo04], ray tracing [Zha02] and physical optics.

4.1.3.1 Empirical and Semi-Empirical Models

There are two approaches to the solution of in-building propagation problems; empirical and deterministic ones. Empirical models are based on radio channel measurements, whereas deterministic models are drawn from the physical propagation effects. Sometimes, semi-empirical models as a combination of the empirical and deterministic models are considered. [Hop99] presents a simple power-law model for power-level calculation inside a building. [Tur93] introduces formulas for building penetration loss calculation obtained from a set of measurements by regression analysis. The input parameters to the model fitted to the measurements are distance between transmitter and receiver, area of the floor and parameter representing number of external building sides seen by the transmitter. A model for building entry loss is proposed in [COS231]. It takes into account various wall types and angle of incidence with respect to the building wall.

4.1.3.2 Deterministic Models

[Sta01] proposes to calculate the field inside a building using Fresnel diffraction integral. The idea is to consider contribution from various apertures forming the external wall-like doors, windows and walls and to calculate the resulting received field as a sum of contributions from these apertures. This approach can be also used for calculation of the received field further into the building across several walls.

Interface method and Ray prolongation method are described in [Los06]. In the case of the Interface method, the external wall of a building is divided into tiles. Received field inside the building is then calculated, by means of ray-tracing, from contributions of each of the tiles. The advantage of the Interface method is that it works for any level of detail of building description from building contours to detailed building plans. The Ray prolongation method considers rays penetrating external wall of a building without stopping on the exterior-interior interface. An interface loss is then added, depending on the building type and material. An in-building loss (dB/m) representing losses along the ray path within the building has also to be added depending on the path length within the building.

Hybrid models encompassing UTD [Kou74] and other full electromagnetic techniques have also been used in indoor propagation modelling. Indoor propagation studies using a combination of the Method of Moments (MoM) [Bac96] and UTD are adopted for example in [Fou00]. Another approach was used in [Wan00] who combined Ray-optical techniques with the Finite-Element Time Domain method (FDTD) [Lau95]. General research trend in ray-tracing tools is to apply acceleration methods to reduce the computation time. A number of acceleration techniques have been proposed in [Agu00]. Another acceleration approach is the use of ray splitting [For98], frustum ray tracing [Suz00] and dominant path [Wol98].

Other analytical methods for outdoor to indoor propagation modelling are MR-FDPF algorithm (Multi Resolution Frequency Domain ParFlow) [Roc06], Transmission Line Matrix method (TLM) [So97, Hoe97] and the Method of Auxiliary Sources (MAS), as proposed in [Zar02], [Zar06].

[Fon06] discusses in detail how to deal with transmission losses through loss-less or lossy dielectric slabs, and how to take into account the humidity and moisture effects.

4.1.3.3 Narroband Partition Loss

[Fon09] lists several empirical models based on propagation measurements to describe the partition loss either on the same floor or between floors within a building.

Linear attenuation model expresses the propagation loss as a sum of free-space loss and a linear term representing the excess loss as a linear function of distance.

One-slope model is based on assumption that propagation loss (in dB) within a building increases linearly with distance [COS231]. Statistical behaviour of the propagation loss is taken into account by adding (as dB units) a normal random variable, derived from measurements. [Sei92a] and [And95] have tabulated the model parameters in various buildings and for different frequencies between 0.9-4.0 GHz.

Floor attenuation factor model is another model taking into account the effect of floor partition losses. The floor attenuation factor is added to the linear attenuation model. [Sei92a] and [Sei92b] have tabulated parameters for this model in various buildings at 914 MHz and q1900 MHz as well.

In Multi-wall model, the path loss is given as a sum of free-space loss and penetration loss through walls and floors. [Fon09] summarises the coefficients for Linear attenuation model, One-slope model and Multi-wall model at 1800 MHz for several types of environments [COS231].

4.1.3.4 Wideband Indoor Models

Most of the multipath propagation models are empirical models based on measurement databases, e.g. [Dev84, Dev87, Nob97, Zha94b]. ITU-R recommendation P.1238-1 [ITU-Rb] assumes the channel impulse response to decay exponentially and presents a model that is normalised by the delay spread. Delay spread values for various indoor environments are tabulated. [Gan91] uses an approach similar to Turin's urban multipath model [Tur72] for modelling the indoor channel, but demonstrates that modified Poisson distribution [Suz77] better represents path arrival times. Saleh-Valenzuela presented a wideband model that takes into consideration the time delay characteristics of received signal was proposed in [Sal87]. The model assumes that the rays associated with the incoming energy arrive in clusters. The Saleh-Valenzuela model has been extended by Spencer et al. [Spe00] to include Angles of Arrival, AoA.

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