Time dynamic channel model for broadband fixed wireless access systems

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Abstract—Broadband fixed wireless access (BFWA) has been recognised as an effective first kilometre solution for delivering broadband services to residential and business customers. The large bandwidths available above 20 GHz make radio systems with very high capacities possible. Users can be offered bit rates in the order of several hundred Mbit/s. Such radio links can, in many cases, be an alternative to optical fibre in terms of capacity. This article presents a time dynamic channel model for BFWA operating above 20 GHz. The developed channel model represents the time varying wideband channel, and combines degradations due to multipath propagation, rain and vegetation attenuation as well as scintillation effects. A time varying tapped delay line model is employed to represent multipath propagation. Time dynamic rain attenuation is modelled using the Maseng-Bakken model. The vegetation attenuation is modelled by a Nakagami-Rice distribution with K-factor decreasing with wind speed. The short term probability density function of amplitude scintillation is modelled by a Gaussian distribution, while the long term distribution is modelled using the Mousley-Vilar model. The combined channel model is suitable for simulating fading mitigation techniques such as adaptive coding and modulation, interference cancellation, and other capacity enhancing techniques.

I. INTRODUCTION

Wireless access systems operating above 20 GHz have wide available bandwidths for delivering broadband triple-play services such as video, audio and data. A high frequency reuse factor is possible and the size of radiating and receiving antennas and electronic components is reduced compared to lower frequency systems. However, millimetre wave signals are more sensitive to propagation degradation due to rain, scintillation and vegetation compared to lower frequency systems. Generally, rain attenuation varies slowly, while vegetation and scintillation effects result in faster signal dynamics. Knowledge of these fast and slow dynamic effects can enable us to predict the maximum data rate supported within different time intervals. This enables data rate adaptation by adjusting coding and modulation to the current channel condition. In this paper we present a wideband statistical channel model which combines the effect of rain, scintillation, vegetation and multipath propagation. This paper is the extension of our earlier work [8], with some improvements of the models and inclusion of scintillation in the combined channel model.

II. DYNAMIC RAIN ATTENUATION

The falling raindrops in the air cause absorption and scattering of the radio waves, and the resulting attenuation shows a considerable temporal and spatial variability. In order to estimate the dynamical channel behaviour, the Maseng-Bakken statistical dynamic model [3] is utilised. This method was originally developed for satellite links, but is easily adapted for terrestrial purposes. The received signal attenuation is modelled as a log-normally distributed variable with a first order power density spectrum. By utilising a memoryless non-linearity the attenuation, \( A(t) \), is transformed into a stationary Gaussian process, \( x(t) \), with zero mean and unit variance:

\[
x(t) = \frac{\ln (A(t)/mA)}{\sigma_A}
\]
where $m_A$ is the median rain attenuation and $\sigma_A$ is the standard deviation of $\ln(A(t))$. The value of the average rain attenuation and standard deviation may be derived from either local measurements of the attenuation distribution or attenuation distributions from ITU recommendation P.530 [9] by applying curve-fitting routines. The mean square error of the complementary cumulative distribution function (CCDF) of estimated rain attenuation and the CCDF of lognormal distribution are minimised to give the best fit.

The autocorrelation function for $A(t)$ is assumed to be a decaying exponential function corresponding to autoregressive process of first order:

$$R_{tt}(\tau) = e^{-\beta|\tau|}$$  \hspace{1cm} (2)

where the time dependence is described by the parameter $\beta$, which is used in a first order autoregressive filter to shape the autocorrelation function. A small value of $\beta$ corresponds to slowly varying rain attenuation. Reference [10] reports values of $\beta$ for a terrestrial link (in the range $1.46 \times 10^{-3} - 18.45 \times 10^{-3}$ $s^{-1}$), which is somewhat larger than $\beta$ values reported for satellite links [3], [4] and [11]. The variation in the results suggests that $\beta$ depends on the local climate as well as the link geometry.

Rain attenuation time series can now be simulated by filtering Gaussian white noise $n(t)$ with first order lowpass filter with impulse response given by:

$$H_r(z) = \frac{1 - \rho^2}{1 - \rho z^{-1}}$$  \hspace{1cm} (3)

where

$$\rho = e^{-\beta\Delta t}$$  \hspace{1cm} (4)

The output from the filter $x(t)$ has zero mean and unit variance and is fed into the memoryless non-linearity $\exp(m_A + x(t)\sigma_A)$, as shown in Fig. 1, where $m_A$ and $\sigma_A$ are optimised lognormal parameters that give best fit between CCDF of estimated rain attenuation and CCDF of lognormal distribution. An example of simulated rain attenuation time series is shown in Fig. 2 (Matlab software is used in all simulations).

![Fig. 1. Dynamic model of rain attenuation (in dB)](image)

III. AMPLITUDE SCINTILLATION

Tropospheric scintillation is a rapid fluctuation of the signal amplitude and phase due to irregularities in the refractive index. The amplitude of scintillations increases with increasing signal frequency, path length, and antenna beamwidth. Mousley-Vilar [5] proposed a model for the long term distribution of scintillation. The model considers that the scintillation amplitude probability density function (PDF) $p(S|\sigma_s)$ as conditionally Gaussian, while the scintillation intensity PDF $p(\sigma_s^2)$ is log-normal distributed (over a period of a month). The short term PDF of amplitude scintillation follows a Gaussian distribution under conditions of constant scintillation intensity (up to 10 minutes) [12].

The power spectrum $W_S(\omega)$ of amplitude scintillation has a lowpass shape. In theory it has a well defined flat region followed by a region with frequency roll-off slope defined as $f^*$, where $s$ is referred to as the spectral slope. Using the Kolmogorov refractive index spectrum, Ishimaru [13] obtained expressions for the two asymptotes, given below:

$$W_S^{0}(\omega) = \frac{0.8506}{\omega t} c_n^2 k^{7/6} L^{11/6}$$  \hspace{1cm} (5)

$$W_S^{\infty}(\omega) = \frac{2.189}{\omega t} c_n^2 k^{7/6} L^{11/6} \left( \frac{\omega}{\omega_c} \right)^{-8/3}$$  \hspace{1cm} (6)

where $C_n^2$ is the refractive index structure parameter (in the range $10^{-10} - 10^{-20}$ m$^{-2/3}$) which can be calculated from meteorological data (pressure, temperature, humidity and wind direction/speed) [14], $\omega_t = V \sqrt{k/L}$ is the Fresnel frequency, $k = 2\pi/\lambda$ is the wavenumber, $L$ is the path length between transmitter and receiver and $V$ is the wind velocity. These two asymptotes meet at the corner frequency $\omega_c$, given by:

$$\omega_c = 1.43 \cdot V \sqrt{k/L}$$  \hspace{1cm} (7)

Since the roll-off slope of amplitude scintillation is typically around -8/3, the power spectral density (PSD) requires a filter of at least third order. The best FIR filter $H_s(z)$ of a given length which matches the expected PSD of scintillation is achieved using the modified Yule-Walker method described in [15]. The approach used for generating short term scintillation time series is shown in Fig. 3.

![Fig. 3. Model for generating clear sky scintillation time series (in dB)](image)

In addition to clear sky scintillation, scintillation occurs simultaneously during rain induced fades. Mattriccianni et al. [16] found a relationship between scintillation standard deviation $\sigma_s(t)$ and rain attenuation $A(t)$ in dB, given by:

$$\sigma_s(t) = C \cdot A(t)^{5/12}$$  \hspace{1cm} (8)
where \( C \) is a constant which depends on frequency. Reported values of \( C \) are 0.039 and 0.056 for 19.77 and 49.5 GHz respectively [16]. During rain, scintillation time series can be generated using the simulator in Fig. 4. Example of simulated scintillation time series during rain is shown in Fig. 5.

**Fig. 4.** Model for generating scintillation time series during rain (in dB)

![Model for generating scintillation time series during rain (in dB)](image)

**Fig. 5.** Simulated scintillation time series during rain, \( R = 30 \text{ mm/h}, L = 2 \text{ km}, f = 40 \text{ GHz} \) and \( C = 0.056 \)

![Simulated scintillation time series during rain, \( R = 30 \text{ mm/h}, L = 2 \text{ km}, f = 40 \text{ GHz} \) and \( C = 0.056 \)](image)

**IV. DYNAMIC VEGETATION EFFECTS**

Vegetation effects can severely limit the performance of BFWA system operating at millimetre wavelengths. Attenuation due to single trees varies significantly with species, whether trees are in leaf or wet [17]. At frequencies above 20 GHz leaves have dimensions large compared to the wavelength and will significantly affect the propagation conditions. A theoretical description of penetration into vegetation is given by the theory of radiative energy transfer [18].

The received signal consists of diffuse and coherent components. The diffuse component is due to propagation through vegetation and the coherent component results from diffraction from the top and side of vegetation as well as a ground reflected wave [19]. The envelope distribution may be modelled by Nakagami-Rice distribution. Some measurement results support this, among them [6], but a variety of other distributions are suggested in the literature e.g. lognormal distribution for the attenuation in dB [20]. The distribution is often described in terms of Nakagami-Rice \( K \)-factor \((K = D^2/2\sigma_v^2))\), where \( D \) denotes the amplitude of the coherent component and \( \sigma_v^2 \) is the variance of the diffuse component. The \( K \)-factor is assumed to decrease exponentially with wind speed, see Fig. 6, for 17 and 12 GHz from [6]. For 42 GHz, the \( K \)-factor is obtained by matching the standard deviation produced by Nakagami-Rice model to that of ITU recommendation P.833 model [19] as function of wind speed, see Fig. 7.

**Fig. 6.** \( K \)-factor as function of wind speed

![\( K \)-factor as function of wind speed](image)

**Fig. 7.** Signal standard deviation as function of wind speed, based on the EU CRABS project measurement results reported in [21]

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The average vegetation attenuation can be determined from the ITU recommendation on vegetation [19]. The time varying fading due to vegetation has previously been modelled utilising oscillating reflectors [21]. It can also be modelled by approximating the typical Doppler spreading of signal due to vegetation by a first order Butterworth filter \( H_v(z) \) with a 3 dB cut-off frequency of 1.5 Hz, resulting in a 40 dB cut-off frequency of about 500 Hz, comparable to the measurement results reported in [7]. The latter approach was adopted in this paper see Fig. 8. In our simulations, the Nakagami-Rice \( K \)-factor as function of wind speed is extracted from Fig. 6 and the average vegetation attenuation is estimated from [19]. Examples of simulated vegetation attenuation time series for low and high wind speeds are shown in Figs. 9 and 10 respectively.

**Fig. 8.** Dynamic model of vegetation envelope (linear scale)

![Dynamic model of vegetation envelope (linear scale)](image)

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From wideband measurements at 30.3 GHz Papazian proposed a tapped delay line model in [1]. Based on measurements at 27.4 GHz, a static tapped delay line model was developed in [2] (this multipath model is adopted in our combined channel model). A flexible multipath channel model is reported in [22]. Based on reported multipath models and measurements, among them [1], [22] and [23], Falconer proposed a multipath channel model in [24]. In the multipath models mentioned above, the average tap gain and delay of each tap is given, while no information is provided on the statistical distribution of individual taps. The first tap, corresponding to the LOS path, is assumed to be constant in the multipath model. The multipath components are usually due to reflections from objects in the vicinity of the receiver [21], and Rayleigh distribution may be assumed for the magnitude $m_n(t)$ of multipath taps.

From wideband measurements at 38 GHz [23], the short term received signal variation (over 1-2 minutes) is described by Nakagami-Rice distribution with $K$-factor varying as function of rain rate $R$ in $mm/h$, given by:

$$ K = K_c - C_r R \ dB $$

(10)

where $K_c$ is a local measured clear sky $K$-factor for a given environment and $C_r$ is a constant which depends on metrological conditions. Reported values of $K_c$ and $C_r$ are 16.88 and 0.04 respectively [23]. The decrease of received signal $K$-factor with rain rate in (10) leads to decreasing power on the LOS component, while increasing power in the multipath components. This is because wet surfaces become better reflectors, which results in increasing reflected power of the specular reflection.

VI. COMBINED CHANNEL MODEL

According to the environment and weather conditions, the individual dynamic models for rain, scintillation, vegetation and multipath can be combined to capture the dynamic effects in real channels. The objective is to specify the relationship between propagation effects and combine them in such a way to give complete channel model suitable for simulating capacity enhancing techniques. Fig. 11 shows the proposed combined dynamic channel model, an example of simulated combined effects is shown in Fig. 12. Each received signal component is represented by time delayed taps. These taps are weighted with the experienced degradations (scintillation, rain and vegetation attenuation) as well as the channel multipath power delay profile. Dependency between rain attenuation and scintillation intensity is incorporated utilising Eq. 8. Similarly, the multipath properties depends on the rain rate through Eq. 10. The combined channel model opens for the possibility of correlated attenuation for the different paths, depending on antenna properties and metrological factors such as rain cell size. However, in this paper we utilise uncorrelated channel tap realisations.

VII. CONCLUSION

This paper presents a time dynamic channel model for BFWA systems. The wideband model combines the effect of
rain, scintillation, vegetation and multipath to give a realistic
dynamic channel model. A time varying tapped delay line
model is employed to represent multipath propagation. The
dynamic rain attenuation is modelled using the Maseng-Bakken
model. The vegetation attenuation is modelled by a Nakagami-

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