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Aeronautical Channel Modeling at VHF-Band

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Abstract—A class of aeronautical wideband channel models is proposed, featuring parking & taxi environments, take-off & landing situations, and en-route scenarios for air-ground links and air-air links. Typical and worst-case parameter sets are suggested, based on published measurement results. The models are suitable for an implementation of simple channel emulators on digital computers or in hardware, and thus may be useful for the validation of future VHF digital aeronautical links (VDL).

I. INTRODUCTION

In response to recommendations made at the International Civil Aviation Organization (ICAO) 1990 Communications/Operations (COM/OPS) Divisional meeting, the Aeronautical Mobile Communications Panel (AMCP) and RTCA Special Committee-172 have undertaken parallel studies to identify methods of improving utilization of the 118-137 MHz frequency band. Several transmission modes have been proposed in the mean time. First hardware solutions have been demonstrated, however, computer simulations are currently difficult to compare since no common aeronautical channel model is available. Most of the open literature on aeronautical channel models focuses on the satellite aircraft channel, see for example [1]-[3], and frequencies above the VHF-band. Concerning VHF air-ground links, at least one stochastic model for the aeronautical radio channel exists [4], but this model considers the Doppler power spectrum only (since the underlying measurement results were based on con-

uous wave signals). It features the en-route situation only, and parameters representing typical or worst case conditions are entirely missing.

Characterizing "the" aeronautical channel is a difficult, non-unique task due to different scenarios (a radio should operate in a slow fading environment at any parking position as well as on air-air links, which is the opposite extreme), due to different types of aircraft (e.g., a helicopter is affected by another Doppler spread than a single-engine airplane), due to the type and arrangement of the antenna(s), etc. Therefore, a stochastic channel model should be as simple but flexible and general as possible.

In this paper, we propose a class of aeronautical channel models, featuring parking & taxi environments, take-off & landing situations, and en-route scenarios for air-ground links and air-air links.

1. suggest typical and worst-case parameter sets, based on published measurement results [5], [6] or empirical data, and finally
2. present a channel emulator [7], which is easy to implement on digital computers or in hardware.

The channel models are wideband stochastic multipath propagation models, characterized by the Doppler power spectrum and the delay power spectrum, i.e., the scattering function [7]. This is a "small-area" characterization, which is representative to evaluate, to validate, and to compare transmission standards. By definition, a "small-area model" is valid within a few dozens of wavelengths. We hope that these models, possibly refined, will eventually serve as a reference for simulations of future VHF digital links or related applications. A similar procedure has been defined in related projects, e.g. in connection with the GSM work (Groupe Spéciale Mobile, later known as the Global System for Mobile Communications), where also suitable channel models have been defined by COST-207 [8] for validation and comparison purposes.

"Large-area" aeronautical models have been considered elsewhere, see e.g. [9]. "Large-area" models take, in addition to multipath propagation, shadowing and other propagation losses into account. Such models may be useful for the link budget design, for the simulation of outage probabilities, or may serve as a basis for traffic models, etc. However, "large-area" models are generally not necessary for the design or validation of physical layer transmission techniques.

The outline of this paper is as follows: In Section II we introduce the class of aeronautical channel models and suggest suitable parameter sets. In Section III we present the channel emulator suitable for simulations. Finally, we will draw the conclusions in Section IV.

1 The air-ground link is defined here to be the link from an aircraft to the tower, whether the aircraft is air-borne or not. The air-air link is defined here to be the link between two aircraft; the aircraft are assumed to be air-borne.
2 "Small-area models" are sometimes called "short-term models". We prefer the first definition, since determining the scattering function requires sufficient averaging.
II. AERONAUTICAL CHANNEL MODELS AND PARAMETERS

According to Bello, the so-called wide-sense-stationary uncorrelated-scattering (WSSUS) channel model provides a useful "small-area" characterization of the diffuse (scattered, reflected) components of multipath radio channels [10]. (A line-of-sight (LOS) path must be separately taken into account, see Section III-B.) The WSSUS model is fully determined by the 2-D delay-Doppler power spectrum \( P(\tau, f_D) \), the so-called scattering function. The scattering function is proportional to the 2-D probability density function \( p(\tau, f_D) \) of the Doppler frequencies and the echo delays: \( P(\tau, f_D) \sim p(\tau, f_D) \).

By definition, \( \tau = 0 \) refers to the LOS path subsequently, i.e., \( \tau \geq 0 \). Hence, \( \tau \) is called excess delay, which is related to the detour distance via \( \tau = \Delta d/v \), where \( c \approx 3 \times 10^8 \) m/s is the speed of light.

The Doppler frequencies are within the range \(-f_{D_{\text{max}}} \leq f_D \leq f_{D_{\text{max}}},\) where the one-sided maximum Doppler frequency, \( f_{D_{\text{max}}} \), is proportional to the carrier frequency, \( f_0 \), and the speed of the aircraft, \( v \): \( f_{D_{\text{max}}} = v f_0 / c \). (These numbers hold for air-ground links. On air-air links, the aircraft speeds would add in the worst case.)

In the following, we will assume that the Doppler power and the delay power spectra are independent: \( P_1(\tau, f_D) = P_1(\tau) \cdot P_2(f_D) \). Given this assumption, it is sufficient to specify the 1-D Doppler power spectrum, \( P_2(f_D) \), and the 1-D delay power spectrum, \( P_1(\tau) \), for the different environments, respectively the corresponding 1-D probability density functions \( p(f_D) \) and \( p(\tau) \). Typical and worst-case parameter sets are suggested as well.

A. Parked & Taxi Scenario (Air-Ground)

Doppler power spectra and delay power spectra are plotted in Fig. 1 and Fig. 2 for both scenarios. The spectra as well as its parameters were specified by COST-207 in [8].

![Fig. 1. Doppler power spectrum and delay power spectrum for parked scenarios (with selected parameters).](image)

### Fig. 1. Doppler power spectrum and delay power spectrum for parked scenarios (with selected parameters).

Both at 137 MHz. As a worst case, 2-D isotropic scattering can be assumed, i.e., the echoes are assumed to arrive equally distributed from all directions within a plane: the beamwidth of the scattered components is 360°. In this case the "classical" Doppler power spectrum applies [8], see Equation (11) in Section III-D. Due to the low Doppler frequencies, the actual shape of the spectrum is only of minor influence. (For 3-D isotropic scattering the Doppler power spectrum would be rectangular with \( |f_D| < f_{D_{\text{max}}} \), which is less critical.)

Delay: For the parking scenario a typical urban environment is proposed, whereas a rural area is assumed for the taxi scenario. Both models were specified by COST-207 [8]. The typical urban environment is the worst case here. Note that 7 μs corresponds to \( \Delta d = 2100 \) m and 0.7 μs corresponds to \( \Delta d = 210 \) m, respectively, compare Fig. 1 and Fig. 2. (The COST-207 models assume UHF-frequencies around 900 MHz. A "re-scaling" of the delay power profile from UHF frequencies to VHF frequencies may be done. However, since inflexion and reflection effects (as a function of frequency) are partly compensating each other, the power delay profile is expected to be similar at both frequency bands. Furthermore, the impact of the delay power profile on the systems performance is, for the parking/taxi scenario, negligible anyway for narrowband (VDL) systems.)

Type of fading: In the worst case, the LOS path is blocked, in which case Rayleigh fading can be assumed. Rician fading is assumed in the rural area environment according to [8].

The problem with this scenario will be the "red light effect", given a narrowband (e.g., 25 kHz) radio system and a single Tx and a single Rx antenna. For the symbol durations specified for future VHF digital links (\( T_s \approx 100 \mu s \) (VDL Mode 3) or \( T_s \approx 50 \mu s \) (VDL Mode 4)), the channel is nearly flat fading (non-frequency-selective), i.e., the channel emulation can be simplified and no linear distortions occur.

The "red light effect" is familiar in the context of VHF/FM mobile radio. The signal strength may fade within half a wavelength. In the context of VDL, the "red light effect" may be compensated by Rx antenna diversity. Optimizing the transmitter position may be not possible for all situations. Further counteractions such as frequency hopping, wideband signal designs or channel coding with interleaving does not apply here.
B. En-route Scenario (Air-Ground and Air-Air)

Type of fading: Typically, the channel consists of a LOS path as well as a cluster of reflected, delayed paths. Therefore, this scenario may be characterized by a two-ray model, shown in Fig. 3. Inspired by [3] and [4] (and due to the lack of further information as well as for simplicity), we propose to model the direct path as a constant process and the diffuse channel component as a Rayleigh process. In [6] Rice factors of \( K \approx 2 \ldots 20 \) dB were determined. \( K = 2 \) dB is the worst case reported. A typical Rice factor is about \( K = 15 \) dB. Note the large variations reported.

\[ E[h_0] = 0 \quad E[h_n^2] = 1 \]
\[ h_n \notin C \]
\[ a, c \in \mathbb{R} \]

Fig. 3. 2-ray model of the aeronautical channel (en-route scenario).

Doppler: The en-route scenario is characterized by fast fading: The specified requirements are \( v_{\text{max}} = 440 \) m/s (850 knots) for air-ground links and \( v_{\text{max}} = 620 \) m/s (1200 knots) for air-air links. Correspondingly, \( f_{\text{max}} = 200 \) Hz respectively \( f_{\text{max}} = 280 \) Hz @ 137 MHz [5]. The minimum Doppler frequency is assumed to be about 8 Hz (32 knots). The scattered components are typically not isotropically distributed, i.e., the beamwidth of the scattered components is less than 360°. In [4], a beamwidth of about \( \beta = 3.5° \) was computed and a corresponding Doppler spectrum was derived, assuming that the scatterers are uniformly distributed within the beamwidth, compare Fig. 4. Due to the lack of further inputs, we adopt this model, see Section III-D. (The model may be improved by assuming 3-D scattering and by assuming Gaussian distributed angles. Also, the beamwidth probably depends on the distance between transmitter and receiver: the beamwidth is likely to decrease with increasing distance.) As a worst case, the direction of LOS path coincides with the heading of the aircraft, whereas the scattered components come from behind. This worst case is assumed in Fig. 5.

Delay: Worst-case echo delays of approximately 200 \( \mu s \) (\( \Delta t = 60 \) km) for air-ground links and up to 1 ms (\( \Delta t = 300 \) km) and more for air-air links are reported in [5]. In [5], worst case echo delays of 6...8 \( \mu s \) (\( \Delta t = 1.8...2.4 \) km) are reported for air-ground links during take-off and landing approaches, where the maximum distance was 10-20 nautical miles from the airport. Note that the latter numbers are considerably smaller.

A simple geometrical analysis reveals that \( \Delta d \approx \pi/c \) for air-ground links and \( \Delta d \approx 2\pi/c \) for air-air links, if one dominant reflector is present, where \( h \) is the flight level. Assuming a typical maximum altitude of 10 km, we obtain \( t_{\text{max}} \approx 33 \mu s \) for air-ground links and \( t_{\text{max}} \approx 66 \mu s \) for air-air links. These values are assumed in the following as typical values, if no nautical miles are taken into account. Given a small Rice factor, the channel appears to be frequency-selective.

Doppler power spectra and delay power spectra are plotted in Fig. 5. The problem with this scenario will be fast fading (particularly for air-air links) as well as frequency-selective fading (particularly for small Rice factors), given the specified VDL parameters and worst case channel conditions.

C. Take-off and Landing Scenario (Air-Ground)

This situation is likely to be a mixture of the taxi scenario and the en-route scenario. The beamwidth of the scattered components is perhaps broader than in the en-route environment but typically may be narrower than in the taxi environment. Typical speeds are about \( v = 30...100 \) m/s. The delay power spectrum is likely to switch from a rural area characteristic towards a two-ray scenario. Since concrete measurement results are not available and since the take-off and landing scenario is unlikely to be the worst case, we will not specify more details here.

III. CHANNEL EMULATION

In this section we present two channel emulators, one for a flat fading channel and one for a frequency-selective fading channel. First, the WSSUS model is reviewed.
A. WSSUS Channel Model

The time-varying impulse response of a WSSUS process can be written as [7]

$$h(t, \tau) = \lim_{N \to \infty} \frac{1}{\sqrt{N}} \sum_{n=1}^{N} \exp \left( j \left( \theta_n + 2\pi f_d \tau \right) \right) \delta(t - \tau_n).$$  

where $t$ is the absolute time and $\tau$ is the excess delay. (In the time-invariant case the impulse response is $h(\tau)$.)

The random numbers $\theta_n (0 \leq \theta_n < 2\pi)$, $f_d (-f_{\text{max}} < f_d < f_{\text{max}})$, and $\tau_n (0 \leq \tau_n \leq \tau_{\text{max}})$ have been generated a-priori, i.e., before the simulation run, where $p(\tau, f_d) \sim P_{\text{d}}(\tau, f_d)$ and $p(\theta) = 1/2\pi$. An intuitive interpretation of (1) is that $h(t, \tau)$ is an incoherent superposition of $N$ echoes, where each echo is characterized by a random phase, $\theta_n$, a random delay, $\tau_n$, and a random Doppler shift, $f_d$, $1 \leq n \leq N$. The factor $\sqrt{1/N}$ ensures that the average power is one; this factor is the same for all echoes and for all spectra. According to the central limit theorem (i.e., when $N > 6$) $h(t, \tau)$ is a complex Gaussian process, therefore its amplitude is Rayleigh distributed.

B. Flat Fading Emulator

The discrete-time flat fading emulator is obtained from (1) by substituting $t = kT_{\text{ms}}$ and $\tau = 0 \forall n$, where $k$ is the time index and $T_{\text{ms}} = T_1/N_{\text{over}}$ is the sample duration ($T_1$: symbol duration, $N_{\text{over}} \geq 1$: oversampling ratio): 

$$h_k = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} \exp \left( j \left( \theta_n + 2\pi f_d kT_{\text{ms}} \right) \right).$$  

About 25 echoes ($N = 25$) are sufficient in order to emulate the channel well, if the parameter set $\{\theta_n, f_d\}$ is generated once before the simulation starts. However, only about 7-10 echoes ($N = 7 - 10$) are sufficient, if new parameter sets are generated from time to time, given the same statistics. That way, the real-time effort can be reduced significantly. (Since the discrete impulse response, $h_k$, jumps when new parameters are generated, carrier and clock synchronization must be acquired in the latter case. This is certainly no problem for packet (or block-oriented) transmission.) The statistics are best, if new parameter sets would be generated for every time-division multiple-access (TDMA) slot, i.e., each TDMA slot would have another channel realization approximating the same Doppler power spectrum.

A Rician channel can be modeled by adding a constant to the Rayleigh process. Let us denote the complex-valued direct (LOS) component by $a \cdot e^{j2\pi f_{\text{DLOS}} kT_{\text{ms}}}$, where $a \in \mathbb{R}$ is the amplitude of the LOS path and $f_{\text{DLOS}}$ is the Doppler frequency of the LOS path, and let us denote the complex-valued multipath component by $c \cdot h_k$, where $c \in \mathbb{R}$ is a constant weighting factor and $E[|h_k|^2] = 1$ (due to the factor $\sqrt{1/N}$). Since the quadrature components of the scattered process are zero-mean, the variance of the multipath components (in-phase plus quadrature phase) is $c^2$. The so called Rician factor, $K$, is defined as

$$K = \frac{a^2}{c^2} \quad \text{or equivalently} \quad K = 10 \cdot \log_{10} \frac{a^2}{c^2} \text{ dB}. \quad (3)$$

Let us denote the complex-valued Rician process by $h_k^{\text{Rice}}$, then we have

$$h_k^{\text{Rice}} = a \cdot e^{j2\pi f_{\text{DLOS}} kT_{\text{ms}}} + c \cdot h_k. \quad (4)$$

If we require that $E[|h_k^{\text{Rice}}|^2] = a^2 + c^2 = 1$, then we obtain the following normalization as a function of the Rice factor:

$$a = \sqrt{\frac{K}{K+1}}, \quad (5)$$

$$c = \sqrt{\frac{1}{K+1}}. \quad (6)$$

In the limit for $K \to 0$ (Rayleigh fading) we get $a = 0$ and $c = 1$, whereas in the limit $K \to \infty$ (AWGN) we obtain $a = 1$ and $c = 0$, respectively.

C. Frequency-Selective Fading Emulator

It is well established that the overall channel of a time-continuous linear transmission system, shown in Fig. 6a, can be exactly represented by the equivalent discrete-time model [11] shown in Fig. 6b. The equivalent discrete-time model comprises pulse-shaping in transmitter and receiver, the physical channel, and sampling. All effects are represented by its complex-valued coefficients. Particularly, the Rx filter may be any linear filter, not necessarily a matched filter. The sampling rate is arbitrary: In Fig. 6 the sampling rate, $1/T_{\text{ms}}$, is equal to the baud rate, $1/T_1$, for example. The equivalent discrete-time model is suitable for computer simulations. In order to model WSSUS channels, no excessive oversampling (in order to represent the delays) is necessary. The discrete noise process in Fig. 6b is obtained by filtering the continuous noise process in Fig. 6a with the Rx filter response, and sampling the result of the convolution. For ideal low-pass filters and square-root raised-cosine filters, for example, the discrete noise process is white within the signal bandwidth.

The intention now is to model the coefficients of the discrete-time channel efficiently without introducing any further simplifications. We do not assume that echo-raster and sampling-raster agree (since a physical channel does not possess an echo-raster). Generally, this leads to correlations between the coefficients, which are included in our formula inherently. The assumption of uncorrelated coefficients, seen in many papers, is a simplification.

Let us denote the coefficients of the equivalent discrete-time model by $h_k(l)$, where $k$ is the time index and $l$ is the tap index, $-L_- \leq l \leq L_+$. The number of coefficients taken into account is $1 + L_- + L_+$. As
a result, we obtain [7]

\[ h_\ell(l) = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} \exp \left( j \phi_n + 2\pi f_D k T_{\text{tmp}} \right) \cdot \]

\[ \cdot g_{\text{total}}(IT_{\text{tmp}} - \tau_n), \]

\[ -L_\ell \leq l \leq L_\ell, \]  

(7)

where \( g_{\text{total}}(\tau) = g_{\text{PRT}}(\tau) * g_{\text{PRT}}(\tau) \) is the overall impulse response of transmitter and receiver. Note that the flat fading case is the special case where \( \tau_n = 0 \) (no delays) and \( l = 0 \) (just one tap).

The average power of the coefficients, \( \rho_l = E[|h_\ell(l)|^2] \), is

\[ \rho_l = \int_0^{T_{\text{tmp}}} p(\tau) |g_{\text{total}}(IT_{\text{tmp}} - \tau)|^2 d\tau, \]

\[ -L_\ell \leq \tau \leq L_\ell, \]  

(8)

where \( p(\tau) = \int_{-f_p}^{f_p} p(f_p) df_p \). The overall pulse, \( g_{\text{total}}(\tau) \), must be normalized so that \( \sum \rho_l = 1 \). About ten to twenty echoes (\( N \approx 10 - 20 \)) are sufficient for aeronautical channel modeling, if new parameter sets are generated from time to time.

As an alternative, if \( g_{\text{total}}(\tau) \) is assumed to be unknown or if the modulation scheme is non-linear (which is the case for CPM schemes proposed for VDL mode 4), the physical channel \( h(\tau, t) \) may be modeled as follows:

\[ y_k = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} \exp \left( j \phi_n + 2\pi f_D k T_{\text{tmp}} \right) \cdot \]

\[ \cdot \sin \left( \frac{\pi (l - \tau_n/IT_{\text{tmp}})}{L} \right) y_{k-l} \]

(9)

where \( \sin(\cdot) \) denotes the nearest integer, and \( \sin(x) = \sin(x/2) \), i.e., \( g_{\text{total}}(\tau) \) is replaced by an ideal low-pass filter of length \( L \) (e.g., \( L \approx 20 \)).

The scenarios in Section II-A and Section II-B may be applied to (2) or (7) or (9) by means of the tool presented now.

D. Examples and Valuation

As discussed in [7], \( \theta_n, f_D, \) and \( \tau_n \) may be generated by a functional transformation

\[ v_n = \theta_n(\pi) = \frac{1}{P_v^{-1}(\pi)}, \]

\[ 1 \leq n \leq N, \]  

(10)

where \( v_n \) is a substitute for \( \theta_n, f_D, \) and \( \tau_n \), respectively, \( u_n \in (0, 1) \) is a random, uniformly distributed input variable produced by a random number generator, and \( g_v(u_n) \) is a memoryless nonlinearity, which is the inverse of the desired cumulative distribution function.

The Doppler power spectra and the delay power spectra suggested in Section II can be generated as follows.

As an example for the Doppler spectrum, consider 2-D isotropic scattering, compare Fig. 1 and Fig. 2:

\[ P_{DF}(f_D) = \begin{cases} \frac{1}{\pi f_{D_{max}} \sqrt{1 - (f_D/f_{D_{max}})^2}} & \text{if } |f_D| < f_{D_{max}} \\ 0 & \text{else} \end{cases} \]

(11)

where \( f_{D_{max}} \) is the maximum Doppler frequency. This is the classical Doppler spectrum derived by R.H. Clarke [12, 13], but sometimes dubbed “Jakes spectrum”. Application of (10) gives

\[ f_{D_{max}} = g_{DF}(u_n) = f_{D_{max}} \cdot \cos(\pi u_n), \]

(12)

where \( 0 \leq u_n \leq 1 \) is uniformly distributed.

If the scattering is 2-D uniform within a narrow beamwidth of, let us say \( \varphi_L < \varphi < \varphi_H \) (where \( \varphi_L \) is the lowest angle and \( \varphi_H \) is the highest angle, compare Fig. 4), we have to distinguish between the following cases:

1. (1) If \( 0 \leq \varphi_L < \varphi_H \leq \pi \) we obtain [4]

\[ P_{DF}(f_D) = \begin{cases} \frac{1}{(\varphi_H - \varphi_L) f_{D_{max}} \sqrt{1 - (f_D/f_{D_{max}})^2}} & \text{if } f_{D_{max}} \cos \varphi_H < f_D < f_{D_{max}} \cos \varphi_L \\ 0 & \text{else} \end{cases} \]

(13)

see Fig. 5.

2. (2) If \( \pi \leq \varphi_L < \varphi_H \leq 2\pi \) we obtain

\[ P_{DF}(f_D) = \begin{cases} \frac{1}{(\varphi_H - \varphi_L) f_{D_{max}} \sqrt{1 - (f_D/f_{D_{max}})^2}} & \text{if } f_{D_{max}} \cos \varphi_L < f_D < f_{D_{max}} \cos \varphi_H \\ 0 & \text{else} \end{cases} \]

(14)

3. All other cases (i.e., if the beamwidth crosses 0 or \( \pi \)) can be constructed by adding the probability density functions (13) and (14), where the terms of the sum have to be weighted according to their likelihood. Example: If \( \{\varphi_L = 0, \varphi_H = \pi/4\} \) and \( \{\varphi_L = 3\pi/4, \varphi_H = \pi\} \), then the first term of the sum must be weighted by 1/3 and the second term must be weighted by 2/3.

(In the derivation of (13) and (14) we used the fact that \( \sin(\cos(x)) = \pi/2 - |x| \) for all \( |x| \leq \pi/2 \). The
area under the probability density function is normalized to be one in (13) and (14). The same spectrum would be obtained for 2-D isotropic scattering when using a beam antenna [13, Fig. 3]. The corresponding nonlinearity for all three cases is

$$f_{D_n} = f_{D_{\text{max}}} = \frac{1}{\tau_{\text{slope}}(1-e^{-x_{\text{max}}/\tau_{\text{slope}}})} e^{-t/\tau_{\text{slope}}},$$

where $0 \leq x_n \leq 1$ is uniformly distributed. In the limit for $\varphi_L = 0$ and $\varphi_H = 2\pi$ (case 3), the "classical" Doppler spectrum is obtained. Note that the same applies for $\varphi_L = 0$ and $\varphi_H = \pi$ (case 1) or for $\varphi_L = \pi$ and $\varphi_H = 2\pi$ (case 2).

As an example for the delay power spectrum, consider a one-sided exponentially distributed random variate, see Fig. 1 and Fig. 2:

$$p_r(t) = \begin{cases} \frac{1}{\tau_{\text{slope}}(1-e^{-x_{\text{max}}/\tau_{\text{slope}}})} e^{-t/\tau_{\text{slope}}}, & \text{if } 0 < t \leq \tau_{\text{max}} \\ 0, & \text{else,} \end{cases}$$

where $\tau_{\text{max}}$ is the maximum delay and $1/\tau_{\text{slope}}$ is the slope. With (10) we obtain

$$\tau_n = \tau - \tau_{\text{slope}} \cdot \log_e \left( 1 - u_n(1 - e^{-x_{\text{max}}/\tau_{\text{slope}}}) \right) \approx -\tau_{\text{slope}} \cdot \log_e (1 - u_n) \text{ for } \tau_{\text{max}} \gg \tau_{\text{slope}},$$

where $0 \leq u_n \leq 1$ is uniformly distributed. Note that for $\tau_{\text{max}} \gg \tau_{\text{slope}}$, the slope, $\tau_{\text{slope}}$, is more important than the maximum excess delay, $\tau_{\text{max}}$.

These examples indicate that the parameters $\tau_n$ and $f_{D_n}$ (representing the excess delays respectively Doppler frequencies of $N$ discrete echoes) can be quite easily generated by feeding a uniformly distributed random variable, $u_n \in (0, 1)$, into a simple nonlinearity (which may be implemented as a table-look-up). Uniform random number generators are usually available on digital computers. Via (10), a frequency-modulated raster is generated inherently, i.e., most echoes are generated near positions where the probability density function has its maximum.

The "classical" flat fading channel emulator consists of a white Gaussian noise source and an FIR or IIR filter. Usually, several independent sources are used to model a frequency-selective fading channel. Compared to this classical approach, the advantages of (2) and (7) are as follows:

- The model is intuitive and general (because it is based on the scattering function).
- The model is always stable (because the equivalent discrete-time channel has an FIR structure. Its coefficients, $h_k(l)$, are not sensitive with respect to quantization effects.)
- The implementation effort is low.
- The model is flexible (because arbitrary delay and Doppler power spectra can be realized, even for strictly bandlimited processes, see (11))
- The model is tunable (e.g., arbitrary Doppler frequencies can easily be handled. Low bandwidths and variable bandwidths are difficult to implement with FIR or IIR filters.)
- Frequency-selective channels can be modeled without imposing further simplifications.
- There is no acquisition time for the computation of the coefficients $h_k(l)$ (as opposed to the "classical" technique).

IV. CONCLUSIONS

In this paper, we
- proposed a class of "small-area" aeronautical channel models, featuring parking & taxi environments, take-off & landing situations, and en-route scenarios for air-ground links and air-air links,
- suggest typical and worst-case parameter sets, based on published measurement results or empirical data, and finally
- present a channel emulator, which is easy to implement on digital computers or in hardware.

We hope that these models, possibly refined, will eventually serve as a reference for simulations of future VHF digital links or related applications. These recommendations are the best that can be made at the present time, but are subject to review in the light of new experimental data.

ACKNOWLEDGEMENT

We acknowledge the comments and support by Dr. Schlereth from DFS, Offenbach, Germany.

REFERENCES