

A WIDEBAND RADIO CHANNEL MODEL FOR SIMULATION OF CHAOTIC COMMUNICATION SYSTEMS

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Abstract - A general purpose wideband radio channel model implemented in MATLAB has been designed specifically for testing the performance of wideband chaotic communication systems utilising a radio interface. The theoretical basis of the model is presented in the paper, as well as a short description of the MATLAB program and some illustrative examples of the output signal under given input signal and channel conditions. The channel model is based on a number of time-varying taps modelling the signal dispersion in a multipath environment. Generation of the tap fading process is implemented using a novel method based on summation of a number of complex phasors.

I. INTRODUCTION

A wideband channel model has been designed in MATLAB at the Helsinki University of Technology, based on the experience gained in channel modelling acquired during the years 1993-1996 within the project SARF (New Radio Communication Systems and their RF-technology) sponsored by the Finnish Academy. The model uses a novel tap generation method, and utilises subroutines written in C language in order to maximise the speed of the program. This model was originally developed for testing chaotic communication systems, but contains all the essential features for general purpose wideband channel modeling and simulation.

The chaotic communication wideband channel model is based on the tapped delay line or FIR (Finite Impulse Response) filter structure presented in Section II, which has been used extensively for simulation of mobile communication systems, regardless the different radio environments (indoor, urban, rural, mobile satellite), different bit rates (several kbit/s to several Mbit/s) and different system technologies (TDMA, CDMA, FDMA) or system concepts (GSM, DECT, IS-54, IS-95, UMTS) existing or conceived. Since the channel modeling is

performed in equivalent low-pass (ELP) signal domain, processing of complex signals is required.

The theoretical background of the model is given in Sections II and III. A general outline of the MATLAB program and some illustrative MATLAB displays of the output signal under given input signal and channel conditions are presented in Section IV. Details of the MATLAB implementation are not considered in this paper.

II. THE FIR FILTER CHANNEL MODEL

A wideband (dispersive) multipath radio channel is generally characterised in complex equivalent low-pass signal domain by a time-variant FIR filter, implemented as a tapped delay line with K complex time-variant tap coefficients $h_k(t)$, $k = 0, 1, \dots, K-1$, as shown in Figure 1.

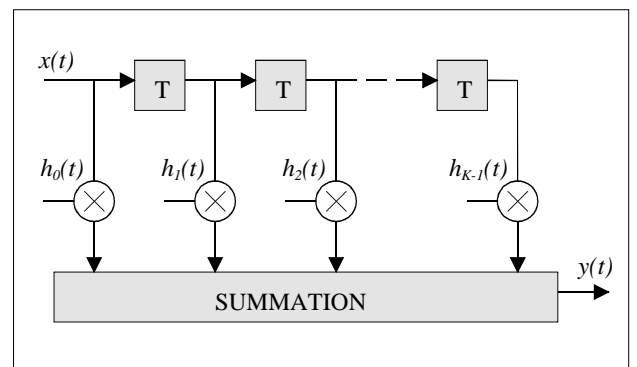


Figure 1: Tapped delay line presentation of a wideband multipath radio channel.

The channel input and output signals are $x(t)$ and $y(t)$, respectively. For some modulation schemes (e.g. binary phase-shift keying, BPSK), $x(t)$ can be chosen real, whereas the tap coefficients $h_k(t)$ and thus $y(t)$ are generally complex. The unit tap delay of the model is

denoted $\Delta\tau$, which must be an integer multiple of the sampling interval T_s of the simulation system (often $\Delta\tau = T_s$). The number of taps K should be chosen such that $(K-1)\Delta\tau$ is equal to or larger than the maximum anticipated delay spread of the radio channel to be simulated.

The tap delays need not necessarily be uniformly spaced. For example, in the GSM TU (Typical Urban) six tap channel model the sampling interval is $0.1 \mu\text{s}$ and the tap delays are at 0, 0.2, 0.5, 1.6, 2.3 and $5.0 \mu\text{s}$ [1]. A tap delay model with non-uniform tap delay spacing corresponds to the uniformly spaced tap delay model shown in Figure 1 where a number of taps are simply set to zero.

According to the theory of communications, the following important relationship must be satisfied in order to avoid aliasing and unrecoverable signal distortion in the A/D and D/A conversion processes [2]

$$\Delta\tau \leq \frac{1}{2B} \quad (1)$$

where B is the bandwidth of the equivalent low-pass signal $x(t)$. To conclude, the signal or system bandwidth and maximum delay spread together determine the number of taps required in the channel model.

It should be noted that the time-variant tap coefficients (tap gains) $h_k(t)$ are complex. The relationship between a real rf signal $s(t)$ and the corresponding complex equivalent low-pass signal (also called the complex envelope) $u(t)$ is [2]

$$s(t) = \text{Re}[u(t)\exp(j2\pi f_c t)] \quad (2)$$

where f_c is the rf carrier frequency. If $x(t)$ is the ELP input signal, the corresponding ELP output signal $y(t)$ from the wideband radio channel characterised by its time-variant ELP impulse response $h(\tau, t)$ is obtained through convolution

$$y(t) = \int_{-\infty}^{\infty} h(\tau, t)x(t-\tau)d\tau = \sum_{k=0}^{K-1} h_k(t)x(t-k\Delta\tau) \quad (3)$$

where the expression on the right hand side can be interpreted as the sum of delayed and time-varyingly weighted replicas of the signal $x(t)$.

III. MODELLING THE TIME-VARIANT TAP GAIN (“TAP FADING”)

In discrete time simulation programs, the tap coefficients $h_k(t)$ are not time continuous, but are instead sequences of complex samples $h_{k,i}$

$$h_k(t) = \sum_{i=-\infty}^{\infty} h_{k,i}\delta(t-iT_s) \quad (4)$$

where $\delta(\cdot)$ denotes the Dirac impulse function.

Since the time constant characterising the channel variation in time domain is orders of magnitude larger than the channel time spread in delay domain (even in high-speed terrestrial mobile radio systems), the tap coefficient samples $h_{k,i}$ need to be updated very infrequently in terms of T_s . Between successive calculated updates, spaced by ΔT , the tap coefficient samples may be interpolated utilising some suitable interpolation algorithm. The upper limit of ΔT is set by the maximum Doppler shift expected in the channel (see below). Like all time or frequency variables, ΔT must be specified in terms of T_s in the MATLAB simulation model.

The Doppler frequency of a propagation path, ν , is related to the linear velocity of motion of the mobile station V , the rf wavelength λ , and the angle α between the direction of motion and the received path, in the following way (see Figure 2)

$$\nu = \frac{V}{\lambda} \cos \alpha \quad (5)$$

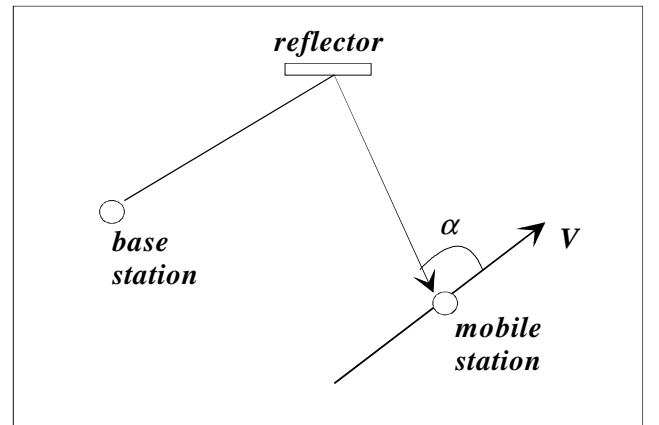


Figure 2: Example for calculating Doppler frequency of a propagation path.

According to the Nyquist sampling criterion, the interval between updates ΔT should be less than the inverse of the total Doppler spread

$$\Delta T < \frac{1}{2\nu_{\max}} = \frac{\lambda}{2V} \quad (6)$$

where ν_{\max} is the maximum possible Doppler shift, equal to V/λ . When there are several unresolved paths contributing to the actual fading of a tap, there are several Doppler frequencies involved. Since these Doppler shifts can not be observed directly, we have to resort to the Doppler spread function $s_k(\nu)$, which is obtained through Fourier transform of $h_k(t)$

$$s_k(\nu) = \int_0^T h_k(t) \exp(-j2\pi\nu t) dt \quad (7)$$

In software simulation, the time dependent fading process of the k :th tap (or the corresponding time domain samples $h_{k,i}$) can be generated in several ways. In this model, a novel approach is used. A number M_k of phasors are generated, where each phasor (representing a propagation path) is rotating in complex plane at a Doppler frequency ν_{km} drawn from a specified Doppler distribution confined to the range $-V/\lambda \dots V/\lambda$. The tap fading as a function of time is simply the complex sum of these phasors,

$$h_k(t) = \sum_{m=1}^{M_k} A_{km} \exp[j2\pi\nu_{km}t + \phi_{km}] \quad (8)$$

where the random variables A_{km} and ϕ_{km} are the phasor amplitudes and initial phasor phases, respectively. The initial phasor phases are essential in order to avoid complete phase alignment between the rotating phasors at time instant $t=0$, and can be randomly chosen from the uniform distribution $(0..2\pi)$.

The choice of distribution(s) for A_{km} , however, is a non-trivial matter. In the MATLAB simulations presented at the end of the paper, the M_k amplitudes of the k :th tap are chosen equal, which to a close approximation results in a Rayleigh envelope distribution of the composite tap fading process when M_k is larger than, say, 6. On the other hand, a specular (or Rician) tap, for instance in case of a line-of-

sight (LOS) channel the tap at $k=0$, is obtained by choosing A_{k0} much larger than the remaining phasors A_{km} , $m \neq 0$. This tap model is versatile since also other tap distributions can be generated, if required.

The mean power of the k :th tap is equal to the sum of the square of the phasor amplitudes

$$P_k = \sum_{m=1}^{M_k} A_{km}^2 \quad (9)$$

where, in a typical wideband radio channel, it can be assumed that the mean power decreases exponentially with increasing tap number. The mean tap powers of the six taps in the GSM TU channel model mentioned in Section II are -3, 0, -2, -6, -8 and -10 dB, respectively.

The Doppler spectrum of the k :th tap simply consists of the power localised at the Doppler frequencies allocated to the M_k phasors

$$S_k(\nu) = |s_k(\nu)|^2 = \sum_{m=1}^{M_k} A_{km}^2 \delta(\nu - \nu_{km}). \quad (10)$$

Often, however, the Doppler spectrum is assumed to be of the form [3]

$$S_k(\nu) = \frac{P_k}{\pi\nu_{\max} \sqrt{1 - \left(\frac{\nu}{\nu_{\max}}\right)^2}} \quad (11)$$

for $-\nu_{\max} < \nu < \nu_{\max}$ and zero otherwise. This spectrum is based on the assumption that the delayed and reflected or scattered signals arrive at the mobile receiver from all directions with equal probability. Theoretically, the Doppler shifts of the M_k unresolvable propagation paths of the k :th tap should be randomly chosen from the U-formed distribution of (11), to be exact, but are chosen in the MATLAB simulation program for simplicity from the uniform distribution $\mathcal{U}(-V/\lambda, V/\lambda)$ without causing significant changes in the average fading behaviour. The assumption leading to (11) is, in practice, rarely fulfilled anyway.

Finally, the M_k phasor amplitudes of the k :th tap are obtained from (9) once the mean tap powers and amplitude distribution(s) are specified. In case of equal amplitudes we simply obtain

$$A_{km} = \sqrt{P_k/M_k}. \quad (12)$$

IV. THE MATLAB CHANNEL MODEL

In the MATLAB channel model, the computational routines in the model are written in C programming language in order to speed up the computations. The built-in capability of MATLAB to exploit C language routines is utilised in form of the mexFunction interface between MATLAB and C code.

The channel model comprises two separate MATLAB mex-files. The file *tapset.mex* sets the initial values for the amplitudes A_{km} , initial phases ϕ_{km} and Doppler frequencies ν_{km} of the phasors employed for generating the tap coefficients. These values are used at the beginning of the simulation.

The file *wchannel.mex* takes care of the actual channel modelling. Samples are taken from the input signal $x(t)$, these samples are then processed utilising the tap coefficients after the predetermined update interval. Since the processing is performed in blocks of a specific length, a signal split up into a set of blocks may contain discontinuities at the block boundaries, due to the memory of the channel. The program is constructed in such a way that this is avoided.

To demonstrate the operation of the MATLAB channel model, the GSM TU (Typical Urban) six tap channel model mentioned in Section II was employed in a test simulation. In this model, the tap delays are at 0, 0.2, 0.5, 1.6, 2.3 and 5.0 μs [1], which leads to a reasonable choice for sampling interval of $T_s = 0.1 \mu\text{s}$. The corresponding tap mean powers are -3, 0, -2, -6, -8 and -10 dB. In order to obtain approximately Rayleigh fading, 5 phasors were chosen for each tap. In this example, for illustrative purpose, a very high relative maximum Doppler frequency of $0.0002/T_s$ was chosen, requiring a small tap updating interval, in this case $32T_s$.

In Figure 3, the complex output signal $y(t)$, in form of real and imaginary parts, is displayed for the case when the input signal $x(t)$ is a constant, real signal of unit amplitude.

Figure 4 shows the impulse response of the simulated channel as a function of time. Each tap fades independently with an approximately Rayleigh distributed envelope. A (narrowband) complex summation of the tap coefficients without taking into account the (wideband)

signal dispersion in form of tap delays results in a similar waveform as that shown in Figure 3.

REFERENCES

- [1] GSM specification 05.05 Annex C, ETSI 1993
- [2] J.G.Proakis: "Digital communications", McGraw-Hill, 1983
- [3] W.C.Jakes: "Microwave mobile communications", Wiley, 1974

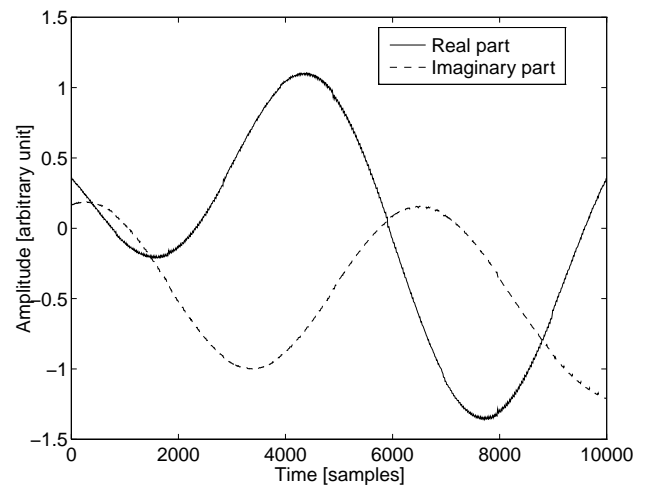


Figure 3: GSM channel simulation output with constant input signal.

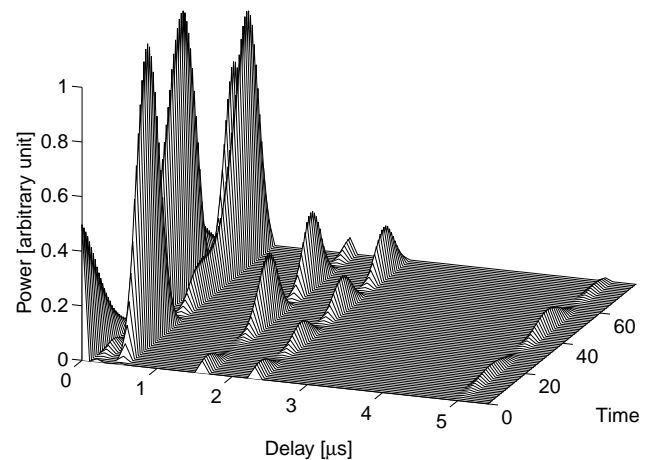


Figure 4: Impulse response of the simulated GSM channel as a function of time (in units of 128 sample intervals).