Statistical characterization of non-WSSUS mobile radio channels

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Dedicated to Univ.-Prof. Dr. Ernst Bonek, on the occasion of his retirement.

In this paper, statistical characterizations of mobile radio channels that do not satisfy the assumption of wide-sense stationary uncorrelated scattering (WSSUS) are discussed, most importantly the local scattering function. The framework presented is particularly suited for doubly underspread non-WSSUS channels. Application examples and measurement results illustrate its practical usefulness.

Keywords: **mobile radio channel; scattering function; channel measurements**

Über die statistische Beschreibung nichtstationärer Mobilfunkkanäle.
In diesem Artikel wird die statistische Beschreibung von Mobilfunkkanälen behandelt, welche nicht die Annahme schwach stationärer unkorrelierter Streuer erfüllen. Besondere Beachtung hierbei findet die lokale Streufunktion. Die vorgestellten Methoden, welche besonders für schwach dispersive und schwach korrelierte Kanäle geeignet sind, werden anhand von Anwendungsbeispielen und Messergebnissen veranschaulicht.

Schlüsselwörter: **Mobilfunkkanal; Streufunktion; Kanalmessung**

1. Introduction and background

1.1 Introduction

Mobile radio channels are characterized by multipath propagation (i.e., delays), Doppler effects (frequency shifts), and fading (stochastic fluctuations) (*Proakis, 1995*). Mathematically, these effects can be captured via random, linear time-varying (LTV) systems. Usually, it is assumed that these channels satisfy the assumption of wide-sense stationary uncorrelated scattering (WSSUS) (*Bello, 1963, Proakis, 1995*). Unfortunately, real-world channels never satisfy the WSSUS assumption in the strict sense. Hence, there is a strong need for a solid theoretical framework for non-WSSUS channels. In this paper, we discuss some recently introduced ideas (*Matz, 2003a, Matz, 2003b*) to statistically characterize non-WSSUS channels and to relate these channel statistics to the mobile radio propagation scenario. Specifically, we present the local scattering function (LSF), the channel correlation function (CCF), the notion of doubly underspread channels, potential applications, and measurement results. We also provide simple guidelines for the local approximation of doubly underspread non-WSSUS channels by WSSUS channels within so-called stationarity regions.

1.2 Related work

There is few existing work dealing with nonstationary channels. The first idea in this direction is the (vague) notion of quasi-WSSUS channels (*Bello, 1963*). The validity of the WSSUS model was scrutinized in (*Kattenbach, 1997*). A discussion of models and simulators for mobile radio channels that take nonstationarities/large-scale effects into account is provided in (*Correia, 2001, Perez, Jimenez, 1994*). Investigation of channel nonstationarity based on similarity measures for successively estimated power delay profiles or MUSIC spectra are given in (*Bultitude et al., 2000, Gehring et al., 2001, Steinbauer, 2001*). Nonstationarity aspects in SIMO and MIMO channels have been studied in (*Herdin, 2004, Utschik, Niering, Hofstetter, 2002*) with a focus on the spatial correlation structure. Correlated scattering was investigated e.g. in (*Dossi, Tartara, Tallone, 1996, Kivinen, Zhao, Vainikainen, 2001*) and implicitly taken into account via vector AR models for the channel taps e.g. in (*Tsatsanis, Giannakis, Zhou, 1996*).

1.3 Characterization of LTV channels

The input-output relation of an LTV channel **H** is (all integrals are from $-\infty$ to ∞)

$$r(t) = (\mathbf{H}s)(t) = \int h(t,\tau)\, s(t-\tau)\, d\tau.$$

Here, $s(t)$ is the transmit signal, $r(t)$ is the received signal, and $h(t,\tau)$ is the impulse response of **H**. Usually, **H** incorporates the effects of antennas and transmit/receive filtering. In fact, this is one of the reasons why **H** might not be WSSUS.

1.4 WSSUS channels

Since the channel **H** is assumed random, its impulse response $h(t,\tau)$ is a 2-D random process. In the simplifying case of a WSSUS channel (*Bello, 1963, Proakis, 1995*), the channel taps $h(t,\tau)$ are stationary in time t and uncorrelated with respect to delay τ, $\mathrm{E}\{h(t,\tau)\, h^*(t',\tau')\} = r_{\mathbf{H}}(t-t',\tau)\, \delta(\tau-\tau')$ (the notation $\mathrm{E}\{\cdot\}$, *, and $\delta(\cdot)$ respectively denotes mathematical expectation, complex conjugation, and the Dirac impulse). The scattering function of the channel, defined as

$$C_{\mathbf{H}}(\tau,\nu) = \int r_{\mathbf{H}}(\Delta t, \tau) e^{-j2\pi\nu\Delta t} d\Delta t,$$

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describes the average power of multipath components with delay τ and Doppler shift ν (*Bello, 1963, Proakis, 1995*).

2. Characterization of non-WSSUS channels

Non-WSSUS channels can be best understood via two dual interpretations. On the one hand, distance-dependent path loss, shadowing, delay drift, changing propagation scenario etc. represent physical mechanisms causing the channel to be nonstationary (WSSUS channels are stationary). On the other hand, multipath components with different delay and Doppler, which are uncorrelated in the WSSUS case, will be correlated for non-WSSUS channels due to reflections by the same physical object and delay/Doppler leakage caused by band- or time-limitations at the transmitter/receiver. This nonstationarity and correlation effects can be described via the local scattering function (LSF) $\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)$ and the channel correlation function (CCF) $\mathcal{A}_{\mathbf{H}}(\Delta t,\Delta f;\Delta\tau,\Delta\nu)$, respectively. These second-order channel statistics are defined as

$$\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)=\iint R_h(t,\tau;\Delta t,\Delta\tau)\, e^{-j2\pi(\nu\Delta t+f\Delta\tau)} d\Delta t\, d\Delta\tau,$$

$$\mathcal{A}_{\mathbf{H}}(\Delta t,\Delta f;\Delta\tau,\Delta\nu)=\iint R_h(t,\tau;\Delta t,\Delta\tau)\, e^{-j2\pi(t\Delta\nu+\tau\Delta f)}\, dt\, d\tau,$$

where $R_h(t,\tau;\Delta t,\Delta\tau)=\mathrm{E}\{h(t,\tau+\Delta\tau)\, h^*(t-\Delta t,\tau)\}$, and Δt, Δf, $\Delta\tau$, $\Delta\nu$ denote time lag, frequency lag, delay lag, and Doppler lag, respectively.

The scattering function of WSSUS channels is independent of time t and frequency f. In fact, in this case the LSF is consistent with the scattering function, $\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)=C_{\mathbf{H}}(\tau,\nu)$. It can furthermore be shown that the LSF describes the average energy transfer between time-frequency locations separated by (τ,ν) and centered about (t,f), or, put another way, the mean power of scatterers causing delay τ and Doppler shift ν at time t and frequency f. Similarly, it can be shown that the correlation of scatterers separated by Δt in time and Δf in frequency and causing delays and Doppler shifts differing by $\Delta\tau$ and $\Delta\nu$, respectively, is characterized by the CCF $\mathcal{A}_{\mathbf{H}}(\Delta t,\Delta f;\Delta\tau,\Delta\nu)$.

It is interesting to note the 4-D Fourier relation

$$\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)=\iiiint \mathcal{A}_{\mathbf{H}}(\Delta t,\Delta f;\Delta\tau,\Delta\nu)\, e^{-j2\pi(t\Delta\nu-f\Delta\tau+\tau\Delta f-\nu\Delta t)}\, d\Delta t\, d\Delta f\, d\Delta\tau\, d\Delta\nu, \qquad (1)$$

which can be viewed as generalized Wiener-Khintchine relation between a power spectrum (the LSF) and a correlation function (the CCF) in the context of non-WSSUS channels. Eq. (1) has important practical implications in that it allows to characterize the coherence and stationarity regions of the channels.

2.1 Coherence region

The channel gain in the time-frequency domain is described by the time-varying transfer function $L_{\mathbf{H}}(t,f)=\int h(t,\tau)\, e^{-j2\pi f\tau} d\tau$. The amount of correlation between transfer function values at time-frequency points separated by Δt and Δf can be shown to be characterized by the spread of the CCF in the Δt and Δf directions. Since (τ,ν) and $(\Delta t,\Delta f)$ are Fourier dual variable pairs, the CCF decay in Δt and Δf depends on the LSF spread in the ν and τ direction, respectively. Measuring the latter in terms of the maximum (effective) Doppler frequency $\nu_{\max}$ and the maximum (effective) delay $\tau_{\max}$, we can define the channel's coherence time and coherence bandwidth as

$$T_c \triangleq \frac{1}{\nu_{\max}}, \qquad F_c \triangleq \frac{1}{\tau_{\max}}.$$

We further define the time-frequency coherence region at (t_0, f_0) as (see Fig. 1)

$$\mathcal{R}_c(t_0,f_0)\triangleq\left[t_0-\frac{T_c}{2}, t_0+\frac{T_c}{2}\right]\times\left[f_0-\frac{F_c}{2}, f_0+\frac{F_c}{2}\right].$$

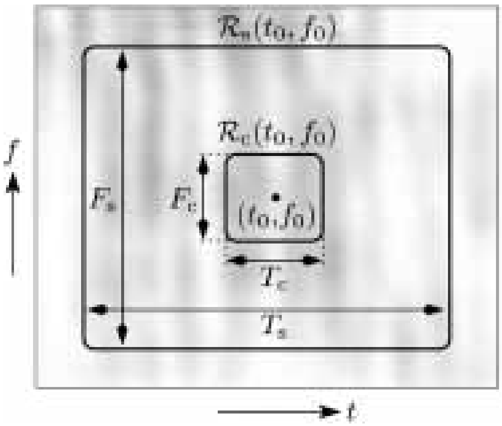


Fig. 1. Schematic illustration of coherence region $\mathcal{R}_c(t_0,f_0)$ and stationarity region $\mathcal{R}_s(t_0,f_0)$

The usefulness of the coherence region is due to the fact that it can be shown that (*Matz, 2003a*)

$$L_{\mathbf{H}}(t,f)\approx L_{\mathbf{H}}(t_0,f_0), \quad \text{for } (t,f)\in\mathcal{R}_c(t_0,f_0),$$

i.e., the transfer function is approximately constant within the coherence region.

2.2 Stationarity region

We next develop novel notions that are characteristic of non-WSSUS channels. Eq. (1) implies that the LSF variation is essentially determined by the CCF spread, in particular the rate of LSF variation in time t and frequency f increases with the extension of the CCF in $\Delta\nu$ and $\Delta\tau$, i.e., with the amount of Doppler and delay correlation. In analogy to the coherence parameters, we next define stationarity parameters for non-WSSUS channels. Assume that the maximum (effective) delay correlation lag is $\Delta\tau_{\max}$ and the maximum (effective) Doppler correlation lag is $\Delta\nu_{\max}$, i.e., $\Delta\tau_{\max}$ and $\Delta\nu_{\max}$ are the largest $\Delta\tau$ and $\Delta\nu$ for which $\mathcal{A}_{\mathbf{H}}(\Delta t,\Delta f;\Delta\tau,\Delta\nu)$ is nonzero. We then define the stationarity time and the stationarity bandwidth, respectively, as

$$T_S \triangleq \frac{1}{\Delta\nu_{\max}}, \qquad F_S \triangleq \frac{1}{\Delta\tau_{\max}},$$

We further define the time-frequency stationarity region at (t_0, f_0) as (cf. Fig. 1)

$$\mathcal{R}_s(t_0,f_0)\triangleq\left[t_0-\frac{T_s}{2}, t_0+\frac{T_s}{2}\right]\times\left[f_0-\frac{F_s}{2}, f_0+\frac{F_s}{2}\right],$$

which is useful since it can be shown that (*Matz, 2003b*)

$$\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)\approx\mathcal{C}_{\mathbf{H}}(t_0,f_0;\tau,\nu), \quad \text{for} \quad (t,f)\in\mathcal{R}_s(t_0,f_0).$$

This means that within the stationarity region the LSF is approximately constant and the non-WSSUS channel can hence be locally approximated by a WSSUS channel $\mathbf{H}_0$ with scattering function $C_{\mathbf{H}_0}(\tau,\nu)=\mathcal{C}_{\mathbf{H}}(t_0,f_0;\tau,\nu)$.

Note that for WSSUS channels all multipath components are uncorrelated. Correspondingly, $\Delta\tau_{\max}=\Delta\nu_{\max}=0$, correctly implying that the stationarity region equals the whole time-frequency plane.

3. Doubly underspread channels

In this section, we discuss the notion of doubly underspread non-WSSUS channels, i.e., channels that are both dispersion underspread and correlation underspread.

3.1 Dispersion and correlation underspread channels

A non-WSSUS channel $\mathbf{H}$ is dispersion underspread if its time-frequency dispersiveness is "small". This means that the extension of the LSF $\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)$ in the τ and ν direction, is small. The LSF extension can be measured by the product $d_{\mathbf{H}} \triangleq \tau_{\max}\nu_{\max}$, of the maximum delay and Doppler (i.e., the largest τ and ν for which $\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)$ is effectively nonzero). We term $d_{\mathbf{H}}$ the channel's dispersion spread. The dispersion underspread property is described by the condition

$$d_{\mathbf{H}} \ll 1. \tag{2}$$

Note that (2) implies $T_c F_c \geq 1$, i.e., the area of the coherence region $\mathcal{R}_c(t_0,f_0)$ is much larger than one. Correspondingly, $L_{\mathbf{H}}(t,f)$ varies only slowly.

Similar to the dispersion underspread property, a correlation underspread property can be formulated that is important to render the LSF $\mathcal{C}_{\mathbf{H}}(t,f;\tau,\nu)$ physically meaningful (*Matz, 2003b*). A non-WSSUS channel is termed correlation underspread if $\mathcal{A}_{\mathbf{H}}(\Delta t,\Delta f;\Delta\tau,\Delta\nu)$ is concentrated about the origin, i.e., if the amount of channel correlation is small. The CCF extension can be measured using a channel correlation spread defined as $c_{\mathbf{H}} \triangleq T_c F_c \Delta\tau_{\max}\Delta\nu_{\max} = \frac{\Delta\tau_{\max}\Delta\nu_{\max}}{\tau_{\max}\nu_{\max}}$. The correlation underspread property then reads

$$c_{\mathbf{H}} \ll 1. \tag{3}$$

For correlation underspread channels, only closely spaced scatterers are correlated. WSSUS channels (with uncorrelated scatterers) are a limiting special case with $c_{\mathbf{H}} = 0$ of correlation underspread channels.

3.2 Doubly underspread channels

We call a non-WSSUS channel doubly underspread if the dispersion underspread property (2) and the correlation underspread property (3) are simultaneously satisfied. This is expressed by the two equivalent double inequalities

$$\Delta\tau_{\max}\Delta\nu_{\max} \ll \tau_{\max}\nu_{\max} \ll 1,$$
$$T_s F_s \gg T_c F_c \gg 1.$$

Hence, the correlation underspread property augments the dispersion underspread property in the sense of additionally requiring that only delay/Doppler components close to each other are correlated. Equivalently, doubly underspread channels have a transfer function that varies only slowly and an LSF that varies even slower than the transfer function. Thus, for a doubly underspread channel the area of the stationarity region is much larger than the area of the coherence region which in turn is much larger than one (see Fig. 1). This property is important in the context of many applications (cf. Sect. 4). Furthermore, it allows for numerically efficient approximations of the LSF, practically important smoothness properties enabling local WSSUS approximations, and structured (Karhunen-Loève) channel expansions (*Matz, 2003b*).

3.3 Example and physical interpretation

To illustrate the practical relevance of the doubly underspread property, we sketch a simple example involving a cellular mobile radio system operating at $f_c = 2$ GHz. Here, a maximum mobile velocity of $\upsilon_0 = 30$ m/s implies a maximum Doppler frequency of $\nu_{\max} = \frac{\upsilon_0}{c} f_c = 200$ Hz and a maximum path length of $d = 1\,500$ m between base station and mobile corresponds to delays of up to $\tau_{\max} = \frac{d}{c} = 5$ µs. Hence, $d_{\mathbf{H}} = 10^{-3} \ll 1$ and the corresponding channels are seen to be dispersion underspread. The coherence parameters are $T_c = 5$ ms and $F_c = 200$ kHz (the coherence region has area $T_c F_c = 10^3 \gg 1$).

Delay-Doppler correlation typically is due to multipath components that correspond to reflections by the same physical object. Scatterers with maximum spatial extention $\omega = 15$ m and maximum angular spread $\delta = 4°$ lead to $\Delta\tau_{\max} = \frac{\omega}{c} = 50$ ns and $\Delta\nu_{\max} = 2\,\nu_{\max}\sin(\delta/2) \approx 14$ Hz. We thus obtain $c_{\mathbf{H}} = 7 \cdot 10^{-4} \ll 1$, verifying that the channels are also correlation underspread. The stationarity region is characterized by $T_s = 1/\Delta\nu_{\max} \approx 72$ ms, $F_s = 1/\Delta\tau_{\max} = 20$ MHz, and an area of $T_s F_s \approx 1.44 \cdot 10^6 \gg T_c F_c = 10^3$. In summary, the channels underlying this scenario are doubly underspread, with each stationarity region containing ≈ 1440 coherence regions.

4. Application examples

We next discuss some potential applications of the foregoing framework in mobile radio systems.

4.1 Channel simulation and performance assessment

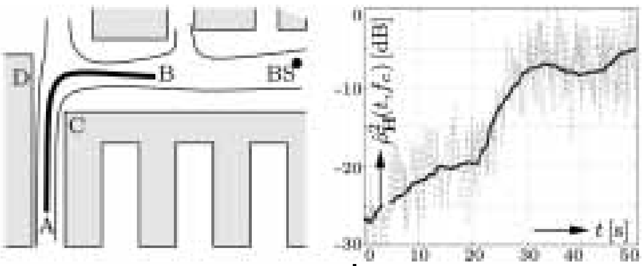
Simulation methods for non-WSSUS wireless channels taking into account channel nonstationarities and multipath correlation are of considerable practical interest for reliable (long-term) performance predictions. An example for long-term performance assessment is given in (*Schafhuber, Matz, 2005*) where the tracking properties of adaptive channel prediction schemes are analyzed using a non-WSSUS channel obtained by a time-dependent convex combination of WSSUS channels. We are currently developing more general and practical non-WSSUS channel simulation schemes by combining the channel simulator from (*Schafhuber, Matz, Hlawatsch, 2001*) with the nonstationary parametric models in (*Jachan, Matz, Hlawatsch, 2003*).

4.2 Ergodic capacity

To achieve the ergodic capacity of wireless fading channels, implicit averaging by coding over numerous independent identically distributed (i.i.d.) fading realizations is required (*Biglieri, Proakis, Shamai, 1998*). Whether sufficient averaging can be achieved depends on the number of i.i.d. fading coefficients offered by the channel. For the flat fading case, independent fading coefficients are obtained every T_c seconds and the fading statistics remain constant over a duration of T_c seconds. Hence, this number approximately equals $\frac{T_s}{T_c}$. Similarly, for doubly dispersive channels, $\frac{T_s F_s}{T_c F_c} = \frac{\tau_{\max}\nu_{\max}}{\Delta\tau_{\max}\Delta\nu_{\max}} = \frac{1}{c_{\mathbf{H}}}$ i.i.d. fading coefficients are offered by the channel. With the example channel of subsection 3.3 there is $\frac{1}{c_{\mathbf{H}}} \approx 1440$, i.e., coding schemes involving enough averaging such that ergodic capacity can be achieved seem realistic for this channel.

4.3 Further potential applications

Our framework is also relevant for transmission methods exploiting delay-Doppler diversity or long-term channel properties in the sense that the limitations of these techniques are captured by our stationarity and correlation parameters. For example, adaptive modulation using channel covariance feedback (e.g., *Boche, Jorswieck, 2002*) is obviously constrained in terms of similar arguments as used previously for ergodic capacity. In a dual sense, the amount of diversity achieved via the multipath-Doppler RAKE receivers in (*Sayeed, Aazhang, 1999*) is limited by the amount of delay and Doppler correlation in the channel. We finally note that well-structured approximate Karhunen-Loève expansions for doubly underspread channels might render the old ideas in (*Chow, Venetsanopoulos, 1974, Kennedy, 1969*) practically feasible.



a **b**

Fig. 2. **a** Channel measurement scenario (gray shading indicates buildings), **b** estimated path gain $\hat{\varrho}^2_{\mathbf{H}}(t, f_c)$ (thick black) and instantaneous path gain (thin gray)

5. Measurement results

To illustrate the practical usefulness of the LSF, we analyse non-WSSUS channel measurements[1]. The measurements were performed in a suburban environment (cf. the propagation scenario in Fig. 2a) at a carrier frequency of f_c=1792 MHz and a bandwidth of $B = 10$ MHz. The base station (labeled 'BS') was fixed and the mobile moved from position 'A' around a corner (labeled 'C') to position 'B' with a constant velocity of 1.6 m/s. All antennas used were omnidirectional, mounted at 3 m (BS) and 2 m (mobile). During the total measurement duration of 50.33 s, impulse response snapshots $h(kT_{\text{rep}}, l/B)$, $k = 1, \dots 1024$, $l = 1, \dots 64$, were recorded ever $T_{\text{rep}} = 49.152$ ms.

The LSF was estimate from a *single* channel measurement using the methods introduced in (*Matz, 2003b*). The resulting LSF estimate $\hat{\mathcal{C}}_{\mathbf{H}}(t, f; \tau, \nu)$, scaled for better display by the time-varying path gain $\hat{\varrho}^2_{\mathbf{H}}(t, f_c) = \int\int \hat{\mathcal{C}}_{\mathbf{H}}(t, f_c; \tau, \nu)\, d\tau\, d\nu$ (cf. Fig. 2b), is depicted in Fig. 3 for fixed $f = f_c$ and for several time instants.

The estimated LSF can be related to the propagation scenario in Fig. 2 and to the mobile movement as follows. During the initial phase the mobile moves through a street towards the corner. Here, shadowing causes a large path loss (cf. Fig. 2b); furthermore, most of the paths arrive through the street ahead of the mobile, leading to angle-of-arrivals (AOA) $\approx 0°$ and corresponding dominant Doppler frequencies close to $\nu_{\max}$ (Fig. 3a, b). The right turn of the mobile at the corner corresponds to a transition phase (Fig. 3c–f). First, AOA and Doppler spread become larger and a multipath component with Doppler frequencies close to 0 Hz (AOA $\approx$ 70–80°) appears (Fig. 3d, e); furthermore, the path loss is significantly reduced (see Fig. 2b). As the mobile finishes its right turn and approaches the base station (Fig. 3f, g), the AOA of the dominant component again drifts towards 0°, eventually resulting in a dominant Doppler component of $\approx \nu_{\max}$ (Fig. 3h). A second Doppler component of $\approx -\nu_{\max}$ with slightly larger delay is due to a building (labeled 'D') located behind the mobile. During the whole measurement period, the delays are seen to drift from ≈ 0.5 μs to ≈ 0.3 μs.

From the LSF estimate, we deduced the coherence parameters $T_c \approx 104$ ms, $F_c \approx 2$ MHz and the stationarity parameters $T_s \approx 2$ s, and $F_s \approx 24$ MHz. The corresponding dispersion and correlation spreads are $d_{\mathbf{H}} = 4.8 \cdot 10^{-6}$ and $c_{\mathbf{H}} = 4.3 \cdot 10^{-3}$, verifying that this channel is doubly underspread.

6. Conclusions

In this paper, we investigated statistical characterizations of non-WSSUS mobile radio channels and their relevance for practical wireless propagation scenarios. The discussion focused on the local scattering function (LSF) and the channel correlation function (CCF) that respectively describe the non-stationary power and the correlation of scatterers (multipath components). The CCF is the basis for the notion of doubly underspread channels that are characterized by small delay-Doppler shifts and a small amount of multipath correlation. The usefulness of the proposed framework is illustrated by application examples and measurement results.

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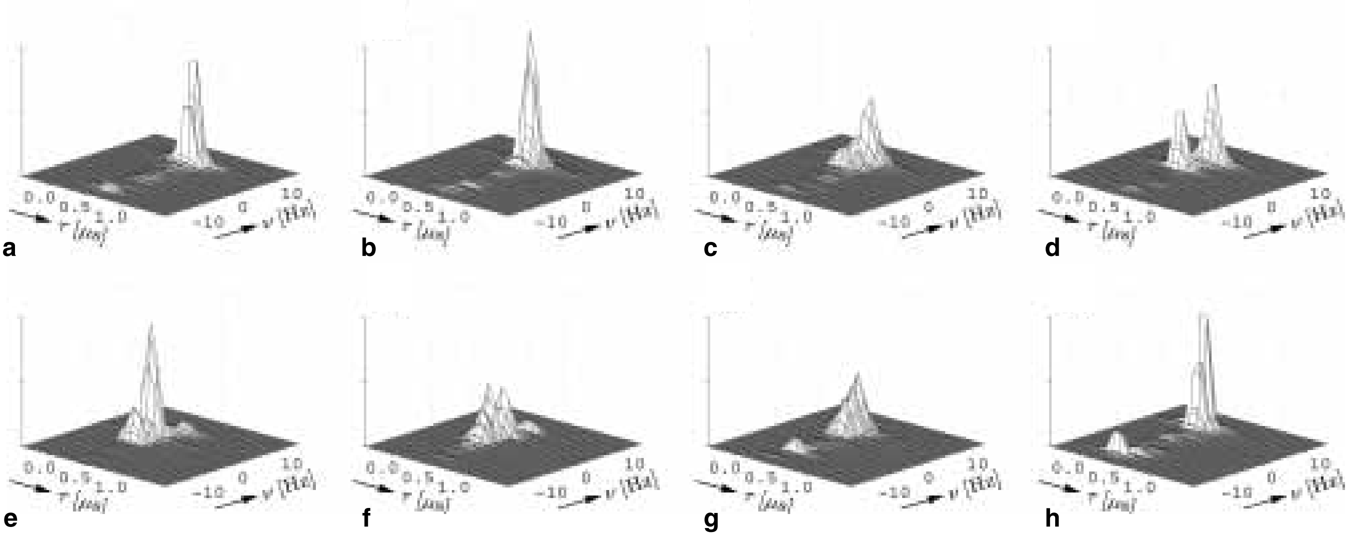

Fig. 3. Eight snapshots of the LSF estimate $\hat{\mathcal{C}}_{\mathbf{H}}(t, f_c; \tau, \nu)$ (normalized by $\hat{\varrho}^2_{\mathbf{H}}(t, f_c)$) for the measured channel with **a** $t = 3$ s, **b** $t = 9$ s, **c** $t = 18$ s, **d** $t = 25$ s, **f** $t = 28$ s, **g** $t = 32$ s, **h** $t = 45$ s

[1] Courtesy of T-NOVA Deutsche Telekom Innovationsgesellschaft mbH (Technologiezentrum Darmstadt, Germany). We are grateful to I. Gaspard and M. Steinbauer for providing us with the measurement data.

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