Statistical Modeling of Small-Scale Fading in Directional Radio Channels

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***Abstract*—After a brief review of the known description of time-variant channels by means of system and correlation functions, a consistent extension of this description to directional time-variant channels is described in the present paper. This extension allows a clear distinction between time- and space-variant effects in directional mobile radio channels. The major intention of the described directional extension however is the derivation of a statistical modeling approach for small-scale fading effects in time-variant wideband directional channels, which can be regarded as a consistent extension of the well established Rayleigh- or Rice-fading approach for nondirectional time-variant narrowband channels. The approach, which is based on the time and aperture-variant transfer function, appears to be preferable to the frequently used statistical modeling of the time-variant angle-resolved impulse response for several reasons. The major advantage is that the approach can cope with the demand for a great number of superimposing components as the basis for statistical modeling. The correlation between adjacent values is proposed to be achieved by filtering with appropriate directional scattering functions. The description of the modeling approach, as done in the present paper, is intended to be general and universal; for the application on certain channel types statistical distribution functions and parameters to be used with the approach can readily be determined from appropriate measurements.**

***Index Terms*—Channel modeling, directional channels, directional WSSUS, small-scale fading, statistical modeling, time-variant channels.**

I. Introduction

SMALL-SCALE fading in multipath channels occurs due to the coherent superposition of a great number of multipath components, each having a different phase variation over time or frequency. The basic and probably mostly well known model for time-variant multipath channels, which has often been called Rayleigh- or Rice-fading model, describes the time-variant fluctuations of the amplitude and phase values by statistical distribution functions. This model originally referred to the fluctuations of a continuous-wave (CW) signal received via a time-variant multipath channel and, thus, basically, it is a narrowband model. For frequency selective (i.e., wideband) channels, a commonly accepted extension of the Rayleigh- or Rice-fading model is the assumption of Rayleigh or Ricean fading for contributions at different delay times in the time-variant impulse response, which results in a tapped delay line model with Rayleigh- or Rice-fading taps.

Since it depends on the bandwidth which components actually superimpose for the different "paths" in the time-variant impulse response, the parameters for the tapped delay line models are however valid only for a certain bandwidth. Even more, since an increasing number of multipath components can be resolved in the time-variant impulse response with increased bandwidth, increasingly less multipath components superimpose and, thus, a statistical modeling of the time-variant fluctuations, which demands for the superposition of a great number of components, becomes questionable. One approach to overcome these disadvantages is a statistical channel model based on the time-variant transfer function, as proposed in [1].

During recent years, the activities in measurement and modeling of radio channels in mobile communications engineering have mainly focused on directional channels, aiming at the development of smart antennas for the capacity enhancement of existing and future systems. Several modeling approaches for directional channels have been presented in the last few years [2], [3]; one that has become very popular is the geometry-based stochastic model [4]. A lot of European work in this field has concentrated in a COST 259 Working Group with the aim to unify different approaches and to find appropriate parameters [3]. Major attention in directional channel description is focused on the appropriate modeling of "azimuth-delay power spectra" (ADPS) by deriving these spectra from spatially random distributed scatterers with certain distributions for different environments. As will be outlined in the present paper, the ADPS contains information about certain "correlations" in the system functions of the channel, but it does not contain information about actually occurring amplitude and phase values in the system functions itself when, e.g., the mobile station or scatterers are moving.

With respect to temporal variations for a moving mobile station, one approach is the assumption of a statistically fading envelope for the components of the time-variant angle-resolved impulse response [5], [6]. As mentioned before, a statistical modeling of temporal variations in the impulse response is questionable however when more and more components are resolved by an increased bandwidth. For directional channel models this problem even increases, since now the components are additionally resolved by their angle of incidence. For a reliable statistical modeling of small-scale variations, thus, another system function has to be taken into account, which can be found from a consistent extension of the ideas in [1] to directional channels, as done in Section II-B of the present paper. This leads to the modeling approach described in Section III, which allows a more universal wideband modeling of directional time-variant channels regardless of their bandwidth.

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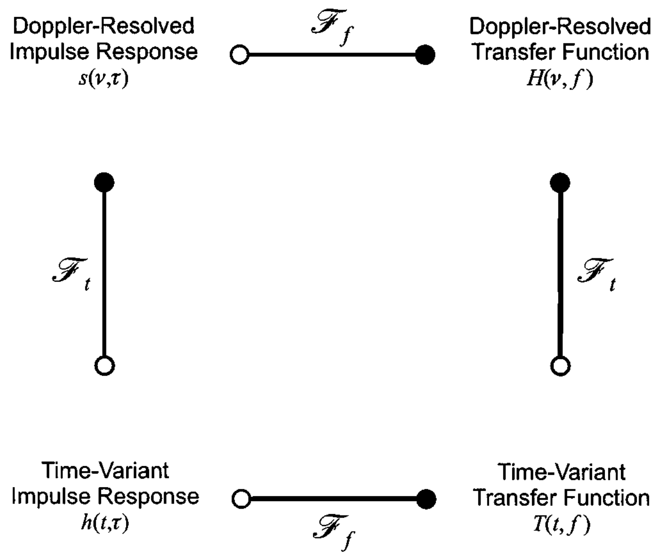

Fig. 1. System functions for time-variant *non*directional channels and their relations by Fourier transforms.

II. System and Correlation Functions

A. Time-Variant Linear Channels

Time-variant linear channels can be described by means of their system and correlation functions. This method of description has first been presented in a complete and evident formulation by Bello [7]. The relations between the system and correlation functions, as far as they are essential for understanding the directional extension in Section II-B, will be briefly reviewed in the following. Note that in view of the interpretation of the system functions in the present paper somewhat different denotations than those introduced by Bello are used. For the correlation functions however, Bello's denotations are kept.

The most popular of the system functions in context with mobile radio channels probably is the *time-variant impulse response* $h(t, \tau)$. From this function, the other system functions can be derived by Fourier transforms with respect to either the time t or the delay τ, such that the four system functions [7], [1] are related to each other by Fourier transforms in a cyclic manner as depicted in Fig. 1. A more detailed investigation of these functions, especially when taking into account the underlying physical propagation process and the results from measurements [1], reveals that for the respective system functions multipath components occur *resolved* with respect to different Doppler shifts ν and different delays τ. With respect to time t or frequency f all unresolved components superimpose coherently, which leads to *time-* or *frequency-variant* fluctuations (fading) due to different variations of the phase of the different components. The "resolution" is always determined by the extent of the observation interval (e.g., during measurement or simulation) with respect to t and f [1]. Taking into account these properties of the system functions and additionally taking into account that for time-*in*variant systems the impulse response and the transfer function are the basic functions, the denotations proposed in Fig. 1 appear to be quite meaningful. The knowledge of at least one of the system functions allows a determination of the output signal of the channel for a known input signal.

Based on each of the four system functions, a related correlation function can be calculated by ensemble averaging [7], [1]. The correlation functions, which are also related to each other by [in the general case two-dimensional (2-D)] Fourier transforms [7], [1], allow a determination of the correlation function of the output signal of the channel if either the input signal or the channel itself is random [7]. Additionally they describe the correlation properties of the system functions.

In context with mobile radio channels usually wide sense stationary uncorrelated scattering (WSSUS) is assumed. This assumption is equivalent to wide sense stationarity with respect to both time t and frequency f [7], [1] when regarding the properties of the *time-variant transfer function* $T(t, f)$. Due to this stationarity the dependence of the *time-frequency correlation function* R_T on four variables in the general case reduces to a dependence on two variables (the time shift Δt and the frequency shift Δf) for a WSSUS channel

$$\begin{aligned} &R_T(t, t'; f, f') = R_T(t, t+\Delta t; f, f+\Delta f) \\ &\rightarrow\ R_T(\Delta t, \Delta f) = E\{T^*(t, f)T(t+\Delta t, f+\Delta f)\} \end{aligned} \quad (1)$$

with $E\{\cdot\}$ being the ensemble average. From the relation between the time-frequency correlation function R_T and the *time-delay correlation function* R_h by a 2-D Fourier transform, the properties of the time-delay correlation function of a WSSUS channel can be derived [7], [1] from (1) as

$$\begin{aligned} R_h(\Delta t; \tau, \tau') &= E\{h^*(t, \tau)h(t+\Delta t, \tau')\} \\ &= \delta(\tau' - \tau) \cdot P_h(\Delta t, \tau) \end{aligned} \quad (2)$$

with $h(t, \tau)$ being the time-variant impulse response. When regarding (2), the WSSUS assumption represents wide sense stationarity (WSS) with respect to time t and uncorrelated scattering (US) with respect to the delay time τ, as expressed by the δ-function in (2). These properties of the time-delay correlation function have led to the designation "WSSUS," since this describes the properties of a WSSUS channel completely in the time domain. The function $P_h(\Delta t, \tau)$ in (2), which is denoted as *delay cross-power spectral density*, is related to the time-frequency correlation function $R_T(\Delta t, \Delta f)$ of a WSSUS channel by an inverse Fourier transform with respect to Δf[1], [7] . Due to the δ-function in (2), the knowledge of the delay cross-power spectral density is sufficient to determine the correlation function. Therefore, $P_h(\Delta t, \tau)$ is often referred to as being a "correlation function" [7] of the WSSUS channel, although in strict sense it is a power spectral density.

The WSSUS assumption has led to a simplification, since now the correlation functions are dependent on two variables rather than four variables in the general case. This leads to simplifications for the input-output relations when using the correlation functions [1], [7]. The other correlation functions of a WSSUS channel can be derived [1], [7] in a quite similar way as (2) and it can be shown [1], [7] that the "correlation functions" are related by Fourier transforms in a cyclic manner as depicted in Fig. 2. Note however, that in strict sense only R_T is a correlation function, whereas P_h, P_H and P_s are power spectral densities.

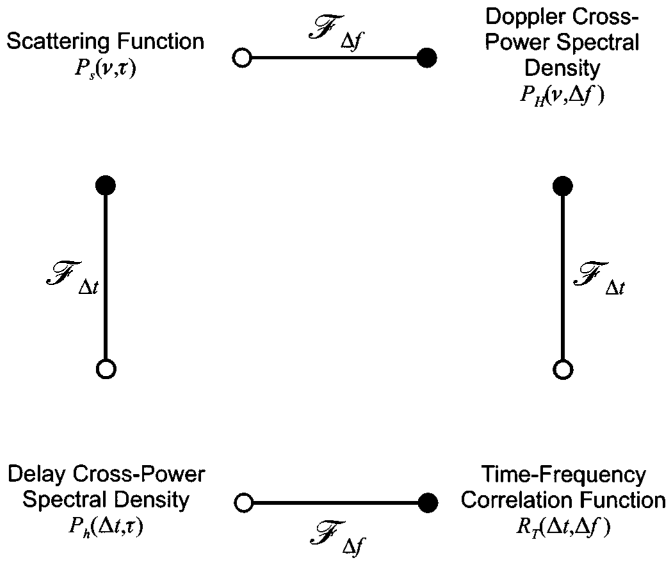

Fig. 2. Correlation functions for time-variant *non*directional WSSUS channels and their relations by Fourier transforms.

B. Extension for Directional Time-Variant Channels

A formal extension of the description methods for time-variant channels to directional time-variant channels is usually done [3]–[5] by introducing an additional dependence of the time-variant impulse response $h(t, \tau)$ on the azimuth angle of incidence φ of multipath components

$$h(t, \tau) \rightarrow h(t, \tau, \varphi) \tag{3}$$

with $h(t, \tau, \varphi)$ being denoted as *time-variant angle-resolved impulse response*. For reasons of clarity, the description of the extension in this paper is confined to the azimuth angle φ at, e.g., the base station. It can additionally be extended in the same manner by the elevation angle ϑ and also by the angles at the mobile station, i.e., $h(t, \tau) \rightarrow h(t, \tau, \varphi_B, \vartheta_B, \varphi_M, \vartheta_M)$. As mentioned in Section II-A, further system functions of time-variant channels can be derived from $h(t, \tau)$ by Fourier transforms with respect to either the time t or the delay τ. Thus, for directional time-variant channels further system functions will result from $h(t, \tau, \varphi)$ by Fourier transforms with respect to either the time t, the delay τ or the angle φ. The relations between time t and Doppler shift ν as well as between frequency f and delay τ will remain the same as for (nondirectional) time-variant channels; thus, we have to consider now the relation resulting from a Fourier transform with respect to φ. It is known from antenna theory that the far-field distribution $E(\sin \varphi)$ is related to the one-dimensional (1-D) aperture distribution $E(x/\lambda)$ by the Fourier transform [8]

$$\begin{aligned} E(\sin\varphi) &= \int_{-\infty}^{+\infty} E(x/\lambda) e^{j2\pi(x/\lambda)\sin\varphi}\, d(x/\lambda) \\ E(x/\lambda) &= \int_{-\infty}^{+\infty} E(\sin\varphi) e^{-j2\pi(x/\lambda)\sin\varphi}\, d(\sin\varphi). \end{aligned} \tag{4}$$

For a finite aperture of extent a equation (4) may be written [8]

$$E(\varphi) = \int_{-a/(2\lambda)}^{+a/(2\lambda)} E(x/\lambda) e^{j2\pi(x/\lambda)\sin\varphi}\, d(x/\lambda). \tag{5}$$

This means for the system functions of directional time-variant channels that a Fourier transform with respect to the angle φ leads to system functions in a domain that can be reasonably denoted as the "aperture domain." Taking into account the linearity of the Fourier transform, multipath components arriving with different angles in the angular domain therefore will superimpose coherently in the aperture domain, which will lead to fluctuations of the absolute value of the system functions over the aperture x. This behavior is dual[1] to the behavior with respect to t and f already described in Section II-A and sketched in Fig. 3. According to that, the denotations and relations from Fig. 1 can be extended to directional time-variant channels in the consistent way given in Fig. 4. Equation (4) reveals that strictly speaking there is a Fourier transform with respect to $\sin\varphi$ rather than with respect to φ. For the resolution of components this will lead to ambiguities of the angle for values of φ outside $-\pi/2 \leq \varphi < \pi/2$, due to the ambiguity of the $\arcsin$-function.

At this point, some interesting conclusions can already be drawn. In the literature on mobile radio channel measurements and modeling there has not always been a strict distinction between time and space, since both are related by the velocity of the mobile station. Some authors have treated the mobile radio channel generally as being space-variant, some generally as time-variant and some have considered the channel to be both. From the fact that the signals transmitted over the channel are time-variant and also from the fact that Bello's description originally has been established for time-variant channels [7], this interpretation may be preferable [1]. Having a closer look at the system functions for directional channels and their relations given in Fig. 4, now there is a clear distinction between time t and space x, with the time being related to the Doppler domain and the space (i.e., the aperture—which actually lies in the spatial domain) being related to the angular domain, each by Fourier transforms. This also means that now there is a clear distinction between angle of incidence of the multipath components and their Doppler shift, which can overcome the problem that the angle of incidence can no longer be identified from the Doppler shift for a channel with moving scatterers. In other words, multipath components with different angles of incidence cause space-variant fluctuations over the aperture even for a time-*in*variant channel (i.e., fixed mobile station and scatterers), whereas Doppler shifts occur even for a nondirectional channel if the channel is time-variant due to a moving mobile station or moving scatterers.

From the duality between the time-Doppler relation, the frequency-delay relation and the aperture-angle relation described before and illustrated in Fig. 3, the relations for WSSUS channels described in Section II-A can be extended straightforwardly

[1]The terms "dual" or "duality" for such analogies in different domains or functions have already been used by Bello in [7] and discussed in more detail in [9].

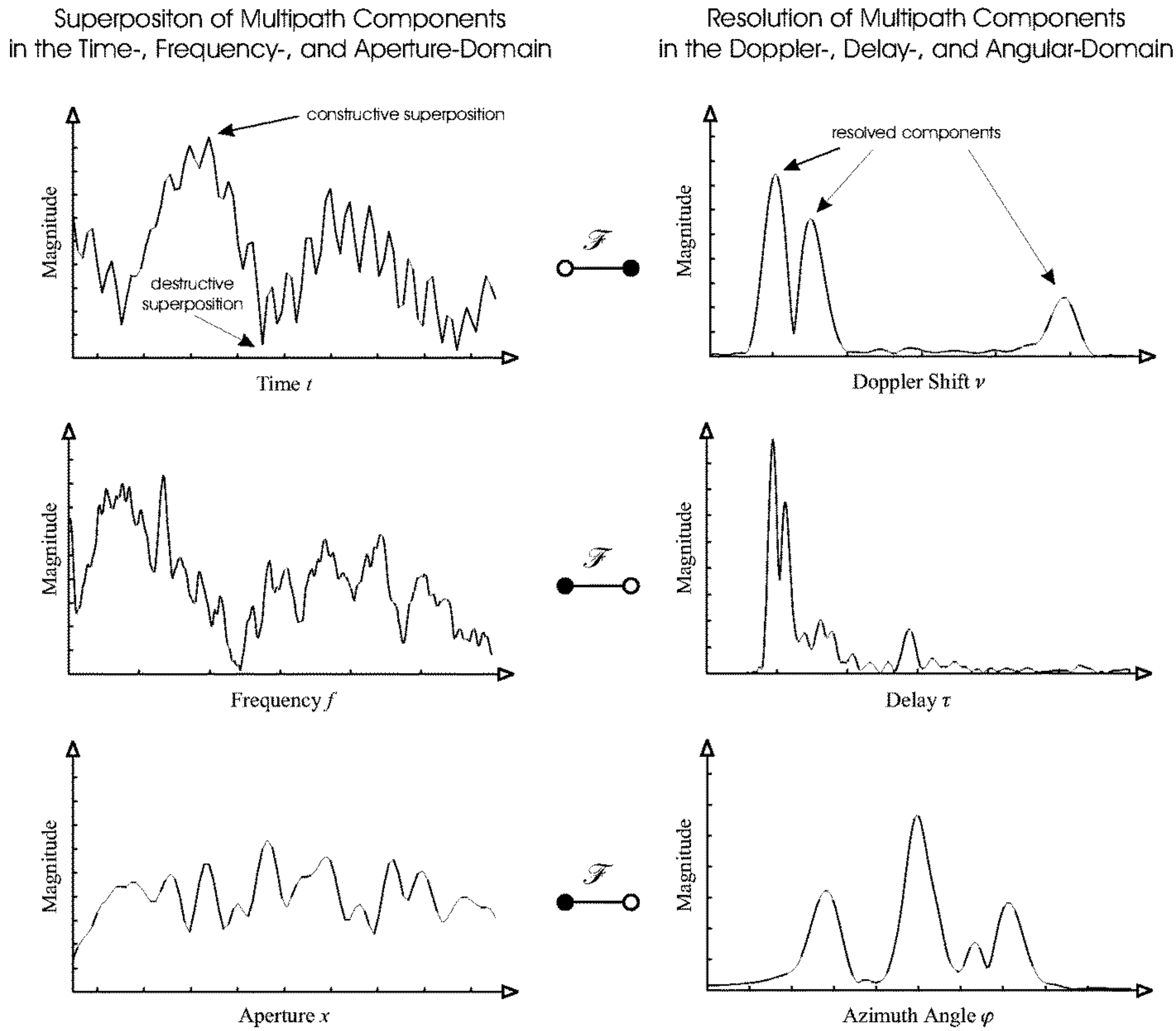

Fig. 3. Superposition and resolution of multipath components in the different domains of directional time-variant channels.

for directional time-variant channels. Since WSSUS channels show uncorrelated scattering with respect to τ and ν a directional WSSUS channel has to show uncorrelated scattering with respect to τ, ν and φ. Thus, for a directional WSSUS channel equation (2) has to be extended as

$$R_h(\Delta t;\, \tau, \tau';\, \varphi, \varphi') = E\{h^*(t, \tau, \varphi)h(t+\Delta t, \tau', \varphi')\} = \delta(\tau' - \tau)\cdot\delta(\varphi' - \varphi)\cdot P_h(\Delta t, \tau, \varphi) \tag{6}$$

with $P_h(\Delta t, \tau, \varphi)$ consequently being denoted as *delay-angle cross-power spectral density*. It has to be noted that due to the aforementioned ambiguity of φ, (6) is valid only in ranges of extent π with $-\pi/2 - n\cdot\pi \le \varphi < \pi/2 - n\cdot\pi$; $n = -\infty, \ldots, -1, 0, 1, \ldots, \infty$, where different power spectral density functions P_{h_n} occur in the different ranges. In practice, however, due to the fact that $\varphi \pm 2\pi = \varphi$, only the two cases $n = 0$ and $n = 1$ (and, thus, two different power spectral density functions) need to be considered.

Since uncorrelated scattering with respect to τ is equivalent to wide sense stationarity with respect to f [1], [7], uncorrelated scattering with respect to φ will result in wide sense stationarity with respect to x, and, thus, (1) will become

$$R_T(\Delta t, \Delta f, \Delta x) = E\{T^*(t, f, x)T(t+\Delta t, f+\Delta f, x+\Delta x)\} \tag{7}$$

for a directional WSSUS channel, with $R_T(\Delta t, \Delta f, \Delta x)$ being the *time-frequency-aperture correlation function*. In the same manner as for (nondirectional) WSSUS channels in [7], [1], the other six correlation functions of a directional WSSUS channel as well as their relations could be derived. However, they can as well be formulated straightforwardly from the dualities described before and, thus, the complete derivations may be omitted here. It turns out that the eight "correlation functions" are related by Fourier transforms as given in Fig. 5.[2] Note again that in strict sense only R_T is a correlation function, whereas P_h, P_m, P_g, P_H, P_M, P_G and P_s are power spectral densities.

[2]A similar figure has been presented in [10] to outline the relations between correlation functions of a directional channel. However, in [10] different but quite meaningful denotations have been used, whereas in Fig. 5 it is attempted to find consistent extensions of Bello's denotations [7].

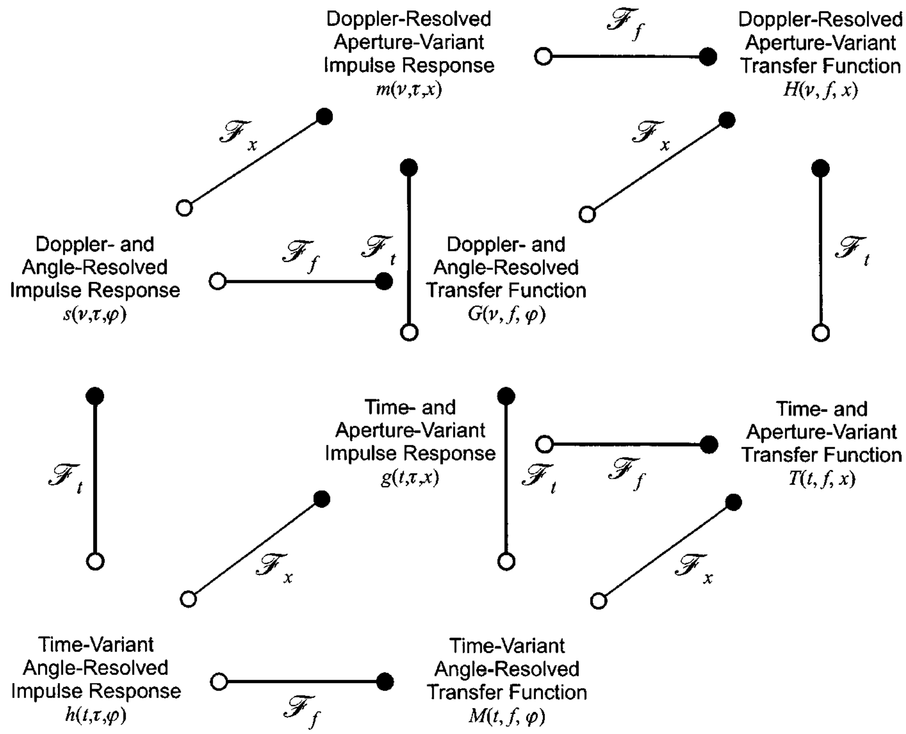

Fig. 4. System functions for time-variant directional channels and their relations by Fourier transforms.

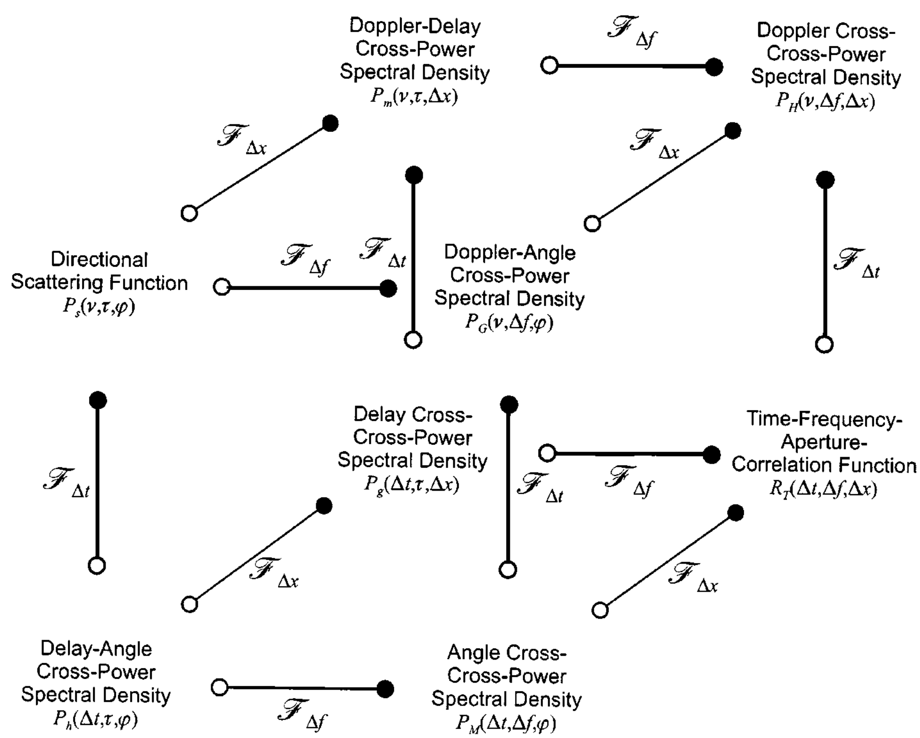

Fig. 5. Correlation functions for time-variant directional WSSUS channels and their relations by Fourier transforms.

The so-called ADPS [3] $P_h(\tau, \varphi)$, which (from extending the nomenclature in [7] to directional channels) should have rather been denoted as delay-angle power density spectrum, is frequently considered in context with directional channel modeling. This function results as a special case of the delay-angle cross-power spectral density $P_h(\Delta t, \tau, \varphi)$ for $\Delta t = 0$ or alternatively by integrating the directional scattering function $P_s(\nu, \tau, \varphi)$ over ν. It is, thus, the directional pendant to the delay power density spectrum $P_h(\tau)$, which has frequently been denoted as "power delay profile" (PDP) [3] in the literature and results from the delay cross-power spectral density $P_h(\Delta t, \tau)$ for $\Delta t = 0$ or alternatively by integrating the scattering function $P_s(\nu, \tau)$ over ν [1]. Since $P_h(\Delta t, \tau, \varphi)$ (and, thus, the ADPS) is related (see Fig. 5) to the time-frequency-aperture correlation function $R_T(\Delta t,\, \Delta f,\, \Delta x)$ by a Fourier transform, the ADPS contains an information about the correlation that occurs with respect to f and x (since $\Delta t = 0$), but it contains no information on actual values occurring in the system functions, as already mentioned in the introduction. Similar to the PDP for nondirectional channels, the ADPS can be interpreted as a kind of "temporally averaged power profile." For many applications, such a temporally averaged channel description may be sufficient. In all other cases, the model has to be extended by explicitly modeling the small-scale and large-scale variations of the system functions either by statistical means or by actually moving the mobile station in the geometry-based stochastic model in [3], [4].

III. Modeling Approach

A. Basic Considerations

As already mentioned in Section I, a widespread and well-accepted mobile radio channel model is the description of temporal variations in the time-variant impulse response by the statistical distribution of amplitude and phase values of the "paths." Consequently, for directional channels it is often proposed (e.g., in [5], [6]) to model the temporal variations of the time-variant angle-resolved impulse response by statistical distribution functions. However, as mentioned before, a wideband statistical modeling of temporal variations in the impulse response is questionable due to its ability to resolve more and more multipath components with increasing bandwidth. If the components are now additionally resolved with respect to their angles of incidence, the number of superimposing components is even less than for the nonangle-resolved case. Since a modeling by statistical distribution functions demands for a superposition of a great number of components, a statistical modeling of temporal variations then becomes even more questionable. Furthermore, since it depends on the bandwidth which multipath components actually superimpose, the parameters of the model are bandwidth dependent.

Basically, each of the system functions is equivalently applicable for modeling. Taking into account the properties of the system functions with respect to the different domains, which have been illustrated in Fig. 3, it turns out that only in the time-frequency-aperture domain there is a superposition of multipath components with respect to all three quantities (t, f and x), whereas for all other domains there is a resolution of components with respect to at least one quantity (τ, ν or φ). Thus, the system function in the time-frequency-aperture domain, i.e., the time- and aperture-variant transfer function $T(t,\, f,\, x)$ obviously is the most appropriate system function for statistical modeling. The time- and aperture-variant transfer function $T(t,\, f,\, x)$ is the counterpart for directional channels to the time-variant transfer function $T(t,\, f)$ for nondirectional channels. Statistical modeling of $T(t,\, f,\, x)$, thus, can be regarded as a consistent extension of the approach in [1] to directional channels.

The strongest argument why to prefer $T(t,\, f,\, x)$ for statistical modeling has already been given before: Since both with respect to t, f and x there is a superposition of components, at each point in the time-frequency-aperture domain the value of $T(t,\, f,\, x)$ will consist of the superposition of *all* multipath components and, thus, the maximum available number, which in practice will be enough to permit a statistical modeling. Due to the fact that at *each* point all components superimpose, the parameters will even be independent of the extent of $T(t,\, f,\, x)$ with respect to t, f and x, as far as large-scale effects (i.e., shadowing and frequency- or distance-dependence of path-loss) are not taken into account.

Another, more intuitive argument is closely related to the first one: Due to the great number of superimposing components a graphically displayed time- and aperture-variant transfer function looks like a "random function," whereas all the other functions look somewhat more deterministic [1]. This can be illustrated by Figs. 6 and 7, which show the absolute value of the time- and aperture-variant transfer function at a fixed point on the aperture and at a fixed instant, respectively, for a measurement in indoor-environment with a synthetic aperture of 1.1 m and three persons acting as moving scatterers. Due to the limited dimensions in graphical display, it is not possible to show the entire time- and aperture-variant transfer function in one graph; however, it is obvious that especially the "random-like" behavior will not change fundamentally for other points in time or space. In strict sense the system functions (or at least one realization) are actually deterministic, otherwise it would not be possible to simulate a mobile radio channel by deterministic means (e.g., ray-tracing). Since it is not possible to exactly determine all mechanisms and parameters for a mobile radio channel, there will of course always be great number of "unknown" components, which can be treated to be random. However, the actual reason why the time- and aperture-variant transfer function looks "random-like" is the superposition of a great number of (deterministic) components.

The third argument is based on the fact that the statistical distribution functions usually taken into account for modeling (i.e., Rayleigh-, Rice-, or Nakagami-distribution) originally have been applied to narrowband modeling. They have been derived from measurements of the time-selective fading for CW signals, i.e., for signals with zero bandwidth. This time-dependent behavior can be found as a 2-D slice of the time-variant transfer function at the respective frequency of the CW signal and, thus, a modeling of the transfer function rather than the impulse response would be the *consistent* extension from narrowband statistical modeling to wideband statistical modeling. From the duality relations described in Section II-B, the counterpart to "zero bandwidth" would be "zero aperture extent." An aperture of extent zero can be identified with a point source, which has an omnidirectional radiation pattern and, thus, describes the nondirectional case. Extending the aperture will result in directional behavior and, thus, a statistical modeling of the time- and aperture-variant transfer function obviously can be regarded as the *consistent* extension from narrowband nondirectional modeling to wideband directional modeling. This can intuitively be interpreted as using several conventional narrowband models for adjacent frequencies at each point on the aperture.

The fourth argument directly results from the duality relations: Due to the time-frequency duality [7], [9], the methods and distribution functions usually applied to statistical modeling

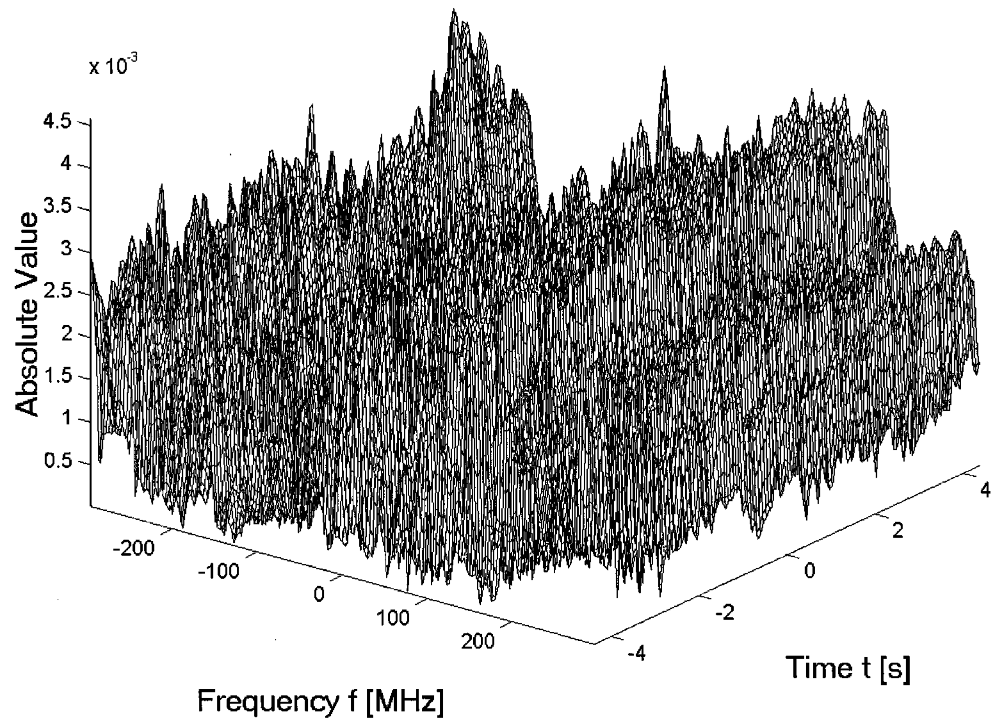

Fig. 6. Time-variant transfer function at a fixed point on the aperture.

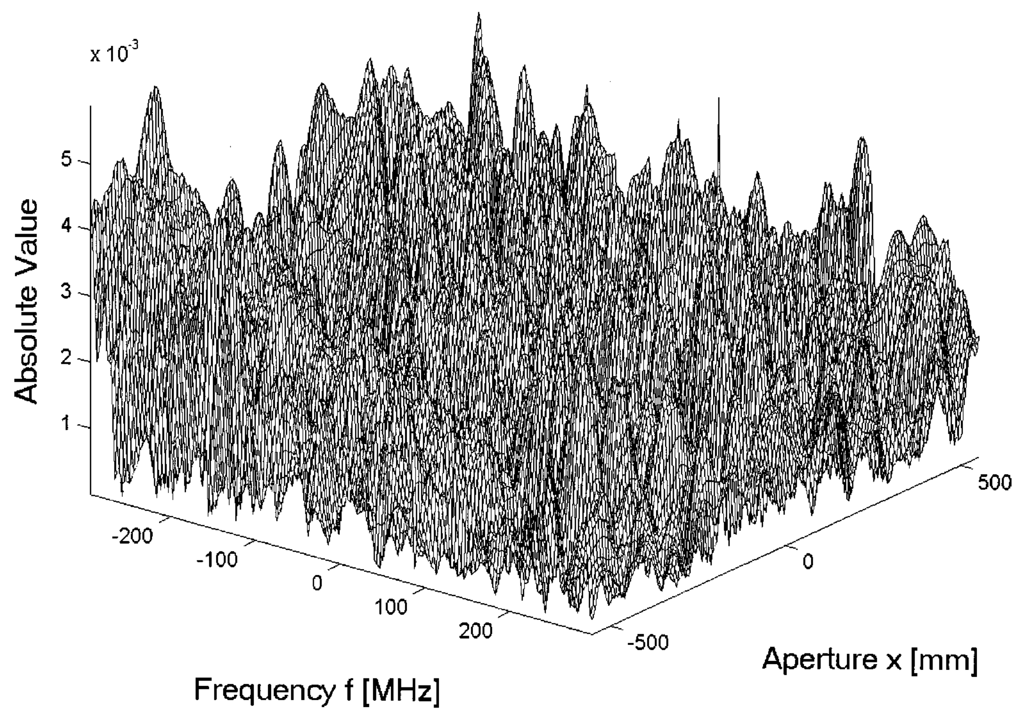

Fig. 7. Aperture-variant transfer function at a fixed point in time.

of the time-selective fading can (and should) be applied as well to the frequency-selective fading. For directional channels the duality can be extended to "time-frequency-aperture duality," since an analogous behavior occurs with respect to the aperture as for time and frequency (see Fig. 3). According to that, the behavior with respect to the aperture can meaningfully be denoted as "aperture-selective fading," which consequently can (and should) be modeled by the same means as the time-selective fading.

B. Proposed Approach

A statistical modeling of the time- and aperture-variant transfer function initially would demand for a three-dimensional (3-D) joint probability density function. However, the approach simplifies, if statistically independent random values are used, since then the joint probability density function can be expressed by the product of the density functions for the time-selective fading, the frequency-selective fading and the aperture-selective fading. From the time-frequency-aperture duality, it can be expected that the distribution functions usually applied for the time-selective fading (i.e., Rayleigh-, Rice-, or Nakagami-distribution) are as well applicable for the frequency-selective fading and the aperture-selective fading.

When using statistically independent random values they are also uncorrelated, which means that initially there is no correlation between adjacent (statistically generated) values of the time- and aperture-variant transfer function. This results in a time-frequency-aperture correlation function $R_T(\Delta t, \Delta f, \Delta x)$ with the shape of a 3-D δ-function. The 3-D Fourier transform yields a directional scattering function $P_s(\nu, \tau, \varphi)$ that is constant for all values of τ, ν and φ, that means, we have a 3-D white process. A white process can be colored by filtering and, thus, in this case, the correlation can be induced straightforwardly by multiplying with a directional scattering function that describes the desired correlation properties of the channel. In fact, this may be regarded as a consistent extension of a method known from narrowband nondirectional statistical models, where the correlation of adjacent values in time is achieved by filtering with appropriate Doppler spectra (e.g., Jakes' spectrum).

The directional scattering function used for the filtering could be generated either purely statistically or purely deterministically; it can also be taken from measurements. Another very attractive way would be the generation of the directional scattering function from the geometry-based stochastic model described in [3], [4], since in fact the directional scattering function is a generalization of the ADPS, as becomes obvious from the description in Section II-B. Due to the ambiguity of φ, which has been mentioned in Section II-B, different directional scattering functions for different ranges have to be used if the angle exceeds the range $-\pi/2 \leq \varphi < \pi/2$.

IV. Conclusion

In the first part of the paper, a directional extension of the channel description by means of system and correlation functions, as known from Bello's frequently cited paper [7], was briefly described. By introducing the angular domain and the aperture domain, which are related by Fourier transform, it is possible to apply certain relations that have already been pointed out by Bello (e.g., WSSUS or the duality relations) straightforwardly to the directional channel description. The extension is consistent with the nondirectional case, since this case is included for an aperture of zero extent, which can be identified as a point source with an omnidirectional radiation pattern. The distinction between time and space (i.e., the aperture) further helps to overcome the questions if, why or when a mobile radio channel should rather be interpreted to be time-variant or space-variant. It can further be expected that the described extension may have even more applications and may help to solve more questions than those in the present paper.

The directional extension of Bello's system and correlation functions has been used in the present paper to apply the ideas in [1] to the statistical modeling of small-scale fading effects in directional channels. The major advantage of the described approach is that it copes with the demand for a great number of superimposing components as the basis for statistical modeling. But also for other reasons, which have been discussed in the present paper, the approach is preferable to the usual approach based on the time-variant impulse response. The approach described in the present paper can be combined with or refine other approaches, for example by the use of directional scattering functions generated by the geometry-based stochastic model in [3], [4].

The description in the present paper intentionally has been kept on a more general and, thus, more universal level. For the application on a certain type of channel, the distribution functions and parameters can readily be determined from appropriate measurements by the same means as already used e.g., for nondirectional indoor radio channels in [1], [11], [12]. The description has also been confined to the modeling of small-scale fading. However, taking into account the duality relations, large-scale fading effects can be incorporated in the model quite easily by superimposing large-scale fading both on the small-scale time-selective, frequency-selective and aperture-selective fading. This allows a modeling of effects like e.g., shadowing of moving scatterers, mobile stations or shadowing of parts of the aperture. Finally, it has to be noted that the description has been confined to the azimuth angle at, e.g., the base station. It can however straightforwardly be extended in the same manner by the elevation angle and also by the angles at the mobile station, which then yields further domains in which there is either a resolution of multipath components with respect to the angle or a superposition with respect to the aperture.

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