

Statistical Analysis of Time-Variant Directional Mobile Radio Channels, Based on Wide-Band Measurements

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Abstract — The paper presents results of a multi-dimensional correlation analysis for time-variant directional mobile radio channels. The study is based on propagation measurements recorded at 5.2 GHz using a wide-band channel sounder together with an 8-element uniform linear antenna array. The underlying parametric signal model is described and based on it, different measured scenarios are investigated with respect to their properties in the delay-Doppler-angular domain. The presented results are well within the expectations and give insight into the propagation mechanisms of directional mobile radio channels.

I. INTRODUCTION

Considerable interest is currently focused on the topic of wireless ATM (asynchronous transfer mode) in order to satisfy the increasing demands for broadband mobile multimedia applications and services. Several projects for studying prototypes of wireless ATM local area networks (LAN) are in progress (e.g. the European ACTS Magic Wand, the IEEE WLAN 802.11, or the ATMmobil project in Germany), accompanied with standardization efforts [1]. One of the systems under consideration is the wireless HIPERLAN/2 approach at 5.15-5.25 GHz offering data rates up to 25 MHz. Generally it is expected that those systems will employ smart antenna principles providing increased capacity and quality of service (QoS) as a result of interference reduction by spatial filtering and sophisticated equalization in the joint time and spatial/angular domain. However, to take advantage of the smart antenna technology, it is necessary to have a thorough understanding of the spatial propagation characteristics of the radio channel [2]. For this reason several measurement campaigns were performed in different scenarios intended for HIPERLAN application (e.g. residential areas, campus-type environments, office buildings, open places, industrial indoor scenarios [3]-[8]). In parallel, numerous channel models were proposed to facilitate simulations and to develop analytical results (overviews can be found in [2],[9]). However, despite those recent achievements there remains a need to gain

deeper insight into the complex mechanisms which govern radio propagation.

This paper expands on some of this recent research. A parametric signal model based on the well-known WSSUS (wide-sense stationary uncorrelated scattering) assumption [10],[11] is described that is used for the statistical analysis of the directional mobile radio channel. In order to provide realistic model parameters propagation measurements have been performed with the RUSK ATM channel sounder at 5.2 GHz employing an 8 element antenna array. The measurement device is described and measurement examples from four different scenarios are presented. Results of the multidimensional correlation analysis related to the temporal, Doppler and angular properties for these four transmission environments are discussed, as well. Finally, in section IV a summary and an outlook are given.

II. SIGNAL MODEL

The signal transmission in a typical mobile radio channel is affected by time-variant multipath propagation. The waves in uplink direction impinging on the base station (BS) antenna aperture consist of a line-of-sight (LOS) component and contributions from $K-1$ non-LOS (NLOS) paths from different directions and with relative excess delays that result from scattering, reflection or diffraction. Time-variance results from movements of the mobile station (MS) as well as environmental objects, causing Doppler shifts and fast fading path weights γ_k . For some limited observation time, the channel impulse response is often considered as wide-sense stationary stochastic (WSS) process. For longer observation periods and MS movement distances of much more than (typically) some tens of the carrier wavelength, the mean path delays τ_k , the directions of arrival (DoA) θ_k , the Doppler shifts α_k and the dominant path numbers K are varying and the r.m.s. path weights become slowly fading. This is due to the changing scenario geometry, possible path shadowing and varying path loss. Thus, the time-space-variant impulse response in the equivalent baseband domain can be given in the following way:

$$h_{t,s}(t, \tau, s) = \sum_{k=1}^K \gamma_k(t) e^{-j2\pi t \alpha_k} e^{-j2\pi s \theta_k} \delta(\tau - \tau_k) \quad (1)$$

with all parameters being considered as valid only in some limited frequency range. For simplification plane wavefronts, narrowband signals and a small antenna aperture are assumed throughout the following considerations. Moreover, we restrict the discussion to only azimuthal DoA's and thus, the space domain is appropriately defined by the linear BS antenna aperture s . The projection of the waves from azimuthal DoA's to the antenna aperture results in the directional cosines $\theta_k = \cos(\theta'_k)$. The parametric linear input/output signal model from (1) can be expressed more clearly when using the appropriate Fourier transform relations

$$\begin{aligned} h(\alpha, \tau, \theta) &= \sum_{k=1}^K (\Gamma_k(\alpha) * \delta(\alpha - \alpha_k)) \delta(\tau - \tau_k) \delta(\theta - \theta_k) \\ H(t, f, s) &= \sum_{k=1}^K \gamma_k(t) e^{-j2\pi t \alpha_k} e^{-j2\pi f \tau_k} e^{-j2\pi s \theta_k} \end{aligned} \quad (2)$$

i.e. the Doppler-azimuth-variant impulse response $h(\alpha, \tau, \theta)$ is related to the time-space-variant frequency response $H(t, f, s)$ by a 3-D Fourier transform. Depending on the available hardware, measurements of the system response functions in (2) can be performed in any domain of the transform pairs.

For our subsequent considerations the well-known WSSUS assumption [10],[11] is adapted. By assuming stationarity with respect to time, frequency and spatial distance ($\Delta t, \Delta f, \Delta s$) a 3-dimensional correlation function can be defined, which corresponds to uncorrelated behavior regarding the variables Doppler, delay and azimuth shift (α, τ, θ). The following 3D-Fourier-Transform relates the expected Doppler-delay-azimuth spectrum to the corresponding expected time-frequency-spatial correlation:

$$\begin{aligned} r(\alpha, \tau, \theta) &= E\{ |h(\alpha, \tau, \theta)|^2 \} \\ R(\Delta t, \Delta f, \Delta s) &= E\{ H(t, f, s) H^*(t + \Delta t, f + \Delta f, s + \Delta s) \} \end{aligned} \quad (3)$$

This general WSSUS relation offers a large variety of deduced functions by applying Fourier transform relations with respect to the different variables. Reduced domain functions and parameters – like the delay-Doppler spectrum, the delay-azimuth spectrum, r.m.s. delay spread, r.m.s. azimuth spread, etc. – can be calculated now by integration over one, two or three variables.

As known from classical spectral estimation of stochastic processes some statistical averaging or smoothing is required in order get stable estimates. The relative variance of the estimation is inversely proportional to some aperture-resolution product. That means, there exists a trade-off between statistical stability and

resolution. From a computational point of view, one possibility is to smooth the rough estimate of the magnitude-squared Doppler-azimuth-variant impulse response by the smoothing window $W(\cdot)$:

$$\hat{r}(\alpha, \tau, \theta) = \iiint W(\alpha - \alpha', \tau - \tau', \theta - \theta') \cdot |h_{TBS}(\alpha', \tau', \theta')|^2 d\alpha' d\tau' d\theta' \quad (4)$$

The index in h_{TBS} denotes a TBS aperture-limited¹ estimate of the Doppler-azimuth variant impulse response from (2). The smoothing impact of $W(\cdot)$ is determined by its spread in the different domains which reveals the compromise between variance reduction and resolution bias. Therefore, the support of $W(\cdot)$ in each of the different domains has to be chosen deliberately in order to match the desired resolution of the path clusters. If the channel has to be evaluated from the viewpoint of some prospective application system, one objective may be to meet the resolution limits of that system. Another estimation possibility is to divide the time sequence $h(t, \tau, \theta)$ with the total aperture record length T into smaller, weighted and overlapping segments and proceed with spectral averaging. In that case, Doppler and delay resolution have to be chosen in advance, but eventually both procedures can be combined effectively [12].

III. MEASUREMENT CAMPAIGNS

Measurement of the time-variant directional structure of mobile radio channels is a necessary prerequisite in order to get direct evidence for the statistical behavior of the temporal, azimuthal and Doppler characteristics in the propagation scenario. For this purpose the RUSK ATM channel sounder [8] has been developed permitting measurements in the 5...6 GHz band. The device consists of a mobile transmitter (Tx) and of a fixed receiver (Rx), acting as the base station. The impulse response identification is based on broadband periodic multi-frequency excitation signals and correlation processing. The 5.2 GHz receiver antenna is formed by an uniform linear array (ULA) of 8 planar antenna elements, which are vertically polarized and have an azimuthal beamwidth of 120°. By fast multiplexing, the elements of the channel response vector snapshot are sequentially estimated from consecutive periods of the transmitted signal. Due to the high measurement bandwidth of 120 MHz and the reasonable array dimensions a large number of different echo paths can be resolved in the joint delay-angular domain. Moreover, the system offers high measurement repetition rates of up to 1 kHz in the standard Doppler mode and up to 78 kHz in the fast Doppler mode, allowing statistical analyses of the channel characteristics, even for

¹ (T, B, S) represent the aperture sizes in the (t, f, s) - domain, with T as time aperture, B as measurement bandwidth and S as maximum antenna aperture. They are limited by signal model restrictions and hardware constraints [8].

dynamic propagation scenarios. For joint delay-DOA estimation an ESPRIT-type algorithm [13] is used in order to achieve superresolution and thus, to overcome resolution limits associated with simple DFT estimation of the discrete parameters in (2). This is important especially for evaluation of micro- and picocell scenarios.

Several propagation measurements have been performed with the RUSK ATM channel sounder lately, covering various scenarios intended for HIPERLAN application. In the following results from measurement campaigns in four different environments are presented, namely within a roofed courtyard, near a junction with heavy traffic, in a suburban residential area, and in an aircraft assembly hangar. For each campaign we focus our attention on one measurement run with moving Tx and fixed Rx, where LOS as well as NLOS situations appear, in order to illustrate the different propagation conditions in each respective environment. Based on a multidimensional correlation analysis with respect to the temporal, Doppler and azimuthal properties the radio wave propagation mechanisms are studied for these four environments.

Scenario I: Courtyard

A measurement campaign was performed in a courtyard at the Ilmenau University of Technology, which was about 37×14 meters in dimension, completely surrounded by buildings and covered by a glass roof. The fixed Rx array was located near a corner within the courtyard, about 1.8 m above the ground and directed toward the inner courtyard. A measurement run was performed through the courtyard starting at the corner, opposite to the Rx position. The Tx was first moved towards the Rx array under LOS and then through a gateway to outside, still under LOS.

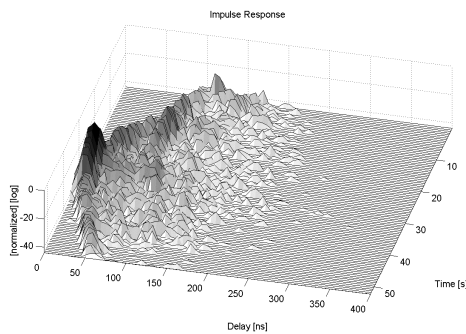


Fig. 1: Instantaneous log-normalized impulse response for the complete measurement run in the courtyard scenario.

In Fig. 1 the instantaneous magnitude-squared impulse response for the complete measurement run, averaged over the 8 array element response vectors is shown. The sequence clearly shows the adequately changing delays. R.m.s. delay spreads and r.m.s. azimuth spreads – which represent a measure for the temporal and angular dispersion of the channel – were calculated for the complete measurement run. Both are shown in Fig. 2. It is interesting to note, that for larger Tx-Rx separations at the

beginning of the record higher delay spreads occur, while for close separations as well as within the gateway the delay spread remains low. Moreover, minimum values of the delay spread remain more or less constant, indicating, that there is a constant, minimum time dispersion. Azimuth spreads are almost completely found in the range between $10 \dots 20^\circ$. However, there are two sections where the azimuth spread falls below this range. The first one is obviously when the Tx passes the Rx and both are separated by approximately only 5 m. The second one happens when the Tx is within the gateway and a waveguiding effect similar to those in tunnels or street canyons occurs [3].

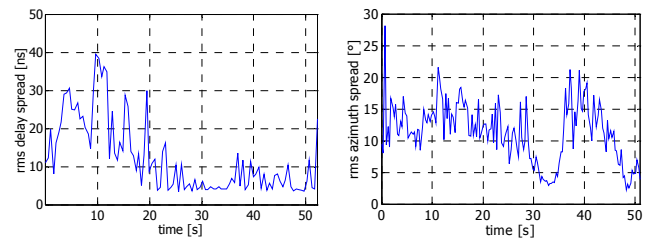


Fig. 2: Instantaneous r.m.s. delay spread (left) and r.m.s. azimuth spread (right) vs. measurement time for the complete measurement run in the courtyard.

Scenario II: Crossroads

To study the propagation behavior of radio channels under the influence of moving scattering objects a measurement campaign was performed near a junction. The measurement place was located in the city of Ilmenau and can be characterized as suburban environment with regular street grid. The Rx array was installed with view across the junction, 1.85 m above the ground. A measurement run was performed starting about 250 m away from the Rx position (for some reasons the measurement run was performed in 3 parts of equal duration). The Tx trolley was moved with walking speed, much slower than the vehicles on the road. At first, the trolley was moved towards the Rx under LOS (often obstructed by vehicles). When the junction was reached the trolley was turned the corner and moved away from the Rx location for about 90 m. At the end of this run there was NLOS connection between Tx and Rx.

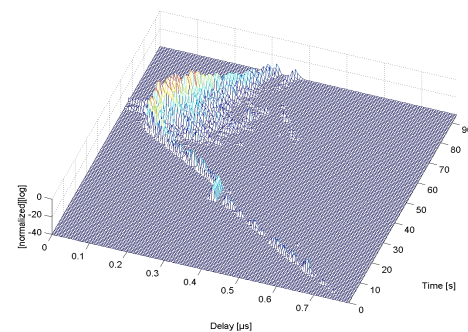


Fig. 3: Instantaneous log-normalized impulse response for the complete measurement in the crossroads scenario.

In Fig. 3 the instantaneous magnitude-squared impulse response for the complete measurement run (all 3 parts together) in the crossroads scenario is shown. R.m.s. delay spreads and r.m.s. azimuth spreads are shown in Fig. 4 for the complete measurement run. Generally, higher delay spreads and higher azimuth spreads occur compared to the courtyard scenario. However, similar to the first scenario there appears a lower bound, where the delay spread never falls below.

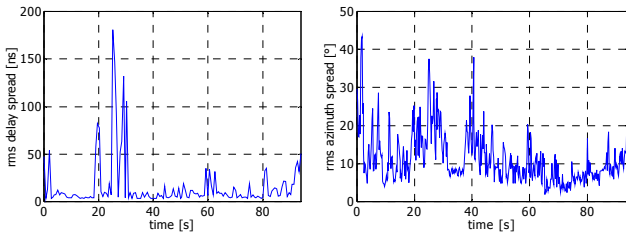


Fig. 4: Instantaneous r.m.s. delay spread (left) and r.m.s. azimuth spread (right) vs. measurement time for the complete measurement run in the crossroads scenario.

In order to characterize the dynamic changes in this scenario delay-Doppler spectra were calculated for two short quasi-stationary sections (about 1 s) during the measurement run. The left part of Fig. 5 figure shows the delay-Doppler spectrum after 25 s of the measurement run, where Tx trolley was moved under LOS towards the Rx location. The right part of Fig. 5 represents this characteristic function for a NLOS situation and Tx movement away from the Rx position (after 89 s, at the end of the measurement run). It turns out that there are several components with nearly the same Doppler shift but at different delays, obviously caused by different vehicles on the road. Both, vehicle movements towards the Rx position as well as away from it can be noticed.

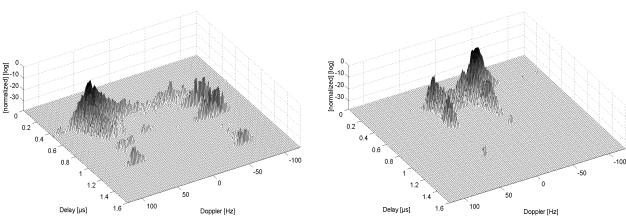


Fig. 5: Delay-Doppler spectra for the measurement run near the crossroad; (left: LOS situation after 25 s; right: NLOS situation after 89 s).

Scenario III: Residential area (suburban)

Recently, a measurement campaign was performed in a residential area in Ilmenau. The environment can be characterized as suburban with a lot of detached houses, but the terrain was quite hilly. The Rx position was chosen near the top of a hill with view over a wide part of the housing estate. A measurement run was performed along a street, about 50 m away from the Rx position. From the viewpoint of the Rx array the Tx trolley was moved from the left to the right side on a distance of about 140 m. In

between the direct LOS path was interrupted several times due to houses along the street. In Fig. 6 the instantaneous log. normalized impulse response for the measurement run in this environment is shown. It indicates that at the beginning of the record there was NLOS situation between Tx and Rx. Then, after approximately 5 seconds there arise two paths – the direct path and a reflected path which is caused by a building. Once the reflected path disappears there arises a new path, due to reflection from another house. This behavior is observed once more here and is typically for residential areas, where the propagation is subjected to shadowing and reflection caused by the buildings.

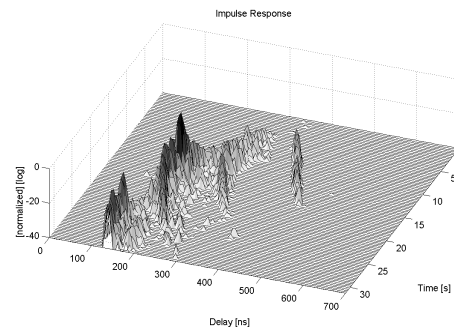


Fig. 6: Instantaneous log. normalized impulse response for the measurement run in the residential area.

Fig. 7 shows the instantaneous r.m.s. delay spread (left) and r.m.s. azimuth spread (right) vs. the measurement time for the complete measurement run in the residential area. Delay spreads are found in a similar range compared to the crossroads scenario and even a constant, minimum delay spread is observed again. However, there are considerable fluctuations of the delay spread due to shadowing and reflections in this environment. Generally, the delay spread tends to vary quicker compared to the azimuth spread. Low azimuth spreads (about 5°) are found only for those situation where obviously LOS propagation was ensured, e.g. during the last 5 seconds of the record.

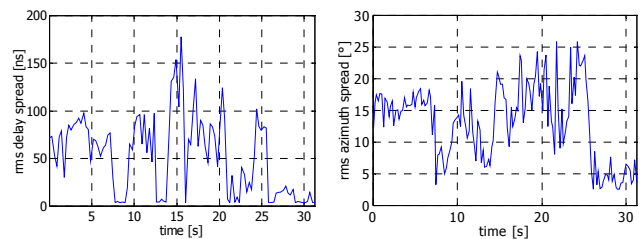


Fig. 7: Instantaneous r.m.s. delay spread (left) and r.m.s. azimuth spread (right) vs. measurement time for the complete measurement run in the residential area.

Scenario IV: Aircraft assembly hangar

Another measurement campaign was performed to study the propagation behavior in dynamic changing scenarios. This campaign took place in an aircraft hangar of the DaimlerChrysler Aerospace AG (DASA) in

Hamburg (Germany). The hall was about $300\text{ m} \times 120\text{ m}$ in dimension, about 30 m in height and covered by a metallic roof. The side walls consisted of large metallic gates. During the measurements about 10 aircrafts/fuselages were arranged in the hangar, representing large reflection objects. Within the hangar there was casual movement of vehicles and persons, but no permanent motion of robots or machines. The Rx array was placed on an aisle about 5.5 m above the ground, providing a good view into a wide part of the hangar. The measurement run was started about 50 m left-hand side from the Rx array. The trolley was moved away from the Rx on a distance of about 140 m , close to a boundary wall of the hangar. In between, the direct LOS path was sporadically obstructed by aircraft bodies.

In Fig. 8 the instantaneous log. normalized impulse response for the complete measurement run in this scenario is depicted. As expected much higher excess delay occur compared to the other three scenarios studied above.

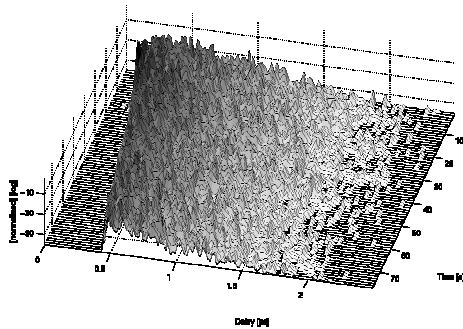


Fig. 8: Instantaneous log. normalized impulse response for the complete measurement run in the industrial scenario.

The instantaneous r.m.s. delay spread and r.m.s. azimuth spread for the complete measurement run in the industrial scenario are displayed in Fig. 9. It can be seen, that for the Tx movement away from the Rx array location the azimuth spread tends to decrease gradually under LOS condition and to increase gradually after transition to NLOS. In contrast, the delay spread changes suddenly for these transitions.

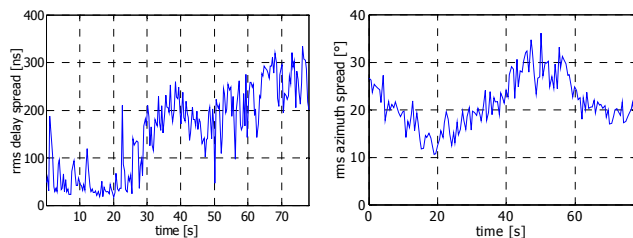


Fig. 9: Instantaneous r.m.s. delay spread (left) and r.m.s. azimuth spread (right) vs. measurement time for the complete measurement run in the industrial scenario.

Interestingly, during the last part of the Tx movement – which apparently was under obstructed LOS condition – the azimuth spread still decreases, while the delay spread

is quite high. However, this measurement run was repeated three times under the same conditions and always equivalent characteristics were observed. Therefore, it is expected that this behavior was caused by a specific feature of the hangar, possibly by a strong reflection via the metallic roof or the metallic gates. This presumption is also encouraged by measurement results at 1.8 GHz , that revealed a strong dependency of the azimuth spread on the environment [14].

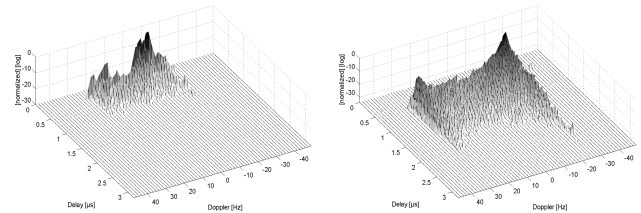


Fig. 10: Delay-Doppler spectra for the measurement run in the industrial scenario; left: LOS situation after 10 s; right: NLOS situation after 70 s.

Fig. 10 shows the delay-Doppler spectra for two quasi-stationary sections (about 1 second) of the Tx trajectory: a LOS situation (left fig.) and a NLOS situation (right fig.). In the NLOS case an almost ideal classical Jakes Doppler spectrum arises. There are, however, also contributions with higher Doppler frequencies than expected from the Tx moving speed as well as from typical velocities in the environment. A first inspection suggested that this effect was caused by fluorescent tubes, that were mounted along the aisle. In fact, this could be verified in a lab experiment recently and is also in accordance with investigations by other research groups [15].

IV. SUMMARY

In this work radio wave propagation at 5.2 GHz was studied based on wide-band measurements with the RUSK ATM channel sounder. Utilizing an 8-element uniform linear antenna array with fast multiplexing of the individual array elements the device has been proven to be very efficient for capturing the time-variant directional structure of the mobile radio channel. In order to perform statistical analysis of the measured data a parametric signal model based on the well-known WSSUS approach has been described. For joint delay-DOA estimation of the impinging waves the unitary ESPRIT algorithm is applied. Results of the correlation analysis in the Doppler-delay-angular domain were discussed for four different measured scenarios intended for HIPERLAN application.

Measurement results indicate that radio wave propagation at 5 GHz is not straightforward. In general, the dispersion in both, temporal and azimuthal domain may become quite high, especially under NLOS condition. Time dispersion varies widely due to the fact that reflections and scattering occur at seemingly random locations, and the resulting multipath channel response appears random, as well. The angular dispersion obviously

depends on the environment between transmitter and receiver antennas, i.e. if there is LOS, NLOS or obstructed LOS condition. In dynamic propagation scenarios (e.g. in industrial environments or near crossroads) instationarities are likely to occur due to movements of vehicles and machines as well as due to shadowing. Moreover, in industrial environments a high percentage of spontaneous time- and loss-sensitive transmissions can be expected. In some cases special propagation effects may occur which have to be taken into account, e.g. waveguiding effects in corridors, or the influence of fluorescent tubes close to the Tx antenna.

The presented results give insight into the behavior of directional mobile radio channels, thus enabling the evaluation and simulation of new communication systems with adaptive antennas. In order to achieve a better statistical reliability of the results a larger number of measurements and propagation studies for a wider range of scenarios is necessary. However, due to the real-time capabilities of the RUSK ATM channel sounder it is a straightforward task to investigate propagation conditions that are non-stationary in the statistical sense. Moreover, estimation of parametric channel models (e.g. [16]) and the usage of measured channel impulse responses for realistic link-level simulation in different scenarios including dynamic changing scenarios is a further issue [17]. Thus, comprehensive sets of standardized and unified channel models can be derived to estimate the capacity and performance of adaptive antenna array systems in a realistic way.

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