Abstract — The simulation of space-time receivers for wireless communication systems requires a spatial channel model which reasonably characterizes the time-variant effects of the mobile radio channel. This paper describes a space-time vector channel model with stochastic fading simulation and its effective implementation for bit-level simulations. Measurements have been analyzed in order to verify the assumptions of the channel model.

I. INTRODUCTION

In order to analyze the performance of new space-time concepts such as adaptive antenna, space-time processing and space-time coding techniques, an adequate space-time channel model is essential. A common channel modeling strategy is the statistical description of time variant fading effects of physical channels due to moving terminals, moving obstacles and the transmission environment [1]. However, those scalar stochastic channel models do not provide any directional information.

To obtain the necessary information about the spatial characteristics of the radio channel geographically based single bounce statistical models (GBSB) can be used [2].

A new combined vector channel model (remote reflectors) with stochastic fading simulation (local scattering) has been introduced [2],[3], based on the assumption, that the multipath propagation is characterized by local scatterers around the mobile station and a few dominant spatially well separated reflectors in the far-field (Figure 1). For each dominant reflector one resolvable path is assumed. This path consists of a large number of incoming waves. These waves result from the structure of local scatterers which are uniformly distributed around the mobile. Since the relative delays of these waves are small with respect to the reciprocal bandwidth of the receiver filter, they cannot be resolved by the receiver. Therefore, they do not need to be resolved in a simulation. In case of any movement in the scenario the superposition of the waves results in Rayleigh-faded paths which are reflected at dominant reflectors. Since the dominant reflectors are significantly separated, a different combination of the incoming rays is reflected at each reflector. Therefore, independent fast fading is assumed for each resolvable path $p$ with a specific time delay $\tau_p$ and AOA $\theta_p$.

Further a different Doppler shift for each path is assumed due to its different relative velocity with respect to a moving transmitter/receiver. Slow fading effects as well as mobile movement including the appearance and disappearance of remote reflectors are also taken into account.

Static and dynamic measurements has been carried out to verify the assumptions of the channel model. Results are presented in section IV.

Fig. 1. Typical local scattering and multipath scenario

II. IMPLEMENTATION

Following we consider a narrow-band space-time channel with one transmit antenna and $M$ receiving antennas. There are multipaths from $P$ dominant reflectors. The received signal at the $m$-th antenna elements is given by:

$$ r_m(t) = \sum_{p=1}^{P} \sqrt{P(\tau_p)} a_p(t) s_m(t - \tau_p) + z_m(t) $$

with $m = 0 \ldots M - 1$, where $\sqrt{P(\tau_p)}$ describes the path attenuation, $s_m(t - \tau_p)$ represents the delayed and phase-shifted transmitted pulse (including path delay and the effects of array propagation) and $z_m(t)$ accounts for interfering waveforms and noise. The time-variant fluctuations
of the path attenuation are modeled using fading coefficients:

\[ \alpha_p(t) = \beta_p(t) \cdot \gamma_p(t). \] (2)

The characteristics of the time-variant channel which further depend on the angle of arrival (AOA) \( \theta_p \) and propagation delay \( \tau_p \) of path \( p \) are described in more detail in the following.

**Path attenuation \( P(\tau_p) \):**

The mean power of each multipath component depends on the propagation delay \( \tau_p \) and is usually defined by a characteristic power delay profile [2].

**Fast fading coefficients \( \beta_p(t) \):**

Fast Fading can be modeled as a Rayleigh-distributed random process. Independent fast fading is assumed for each resolvable path \( p \) with a specific time delay \( \tau_p \) and AOA \( \theta_p \). The Rayleigh-fading coefficients, are generated from a complex Gaussian random process which is filtered using an IIR-Filter with the typical Jakes-Spectrum [1].

**Slow fading coefficients \( \gamma_p \):**

Measurements have shown that the shadowing coefficients \( \gamma_p \) are log-normal Gaussian distributed with a variance \( 3 < \sigma_\gamma < 10 \text{dB} \). The time correlation of \( \gamma_p \) is not known in general. However, measured data in [4] suggest that it can be modeled as simple decreasing correlation function. This can be done using a simple first order unity-energy IIR filter with a pole at

\[ b = \varepsilon \frac{1}{\tau_p}, \] (3)

where \( \varepsilon \) is the spatial correlation between two points separated by a distance \( D, f_s \) defines the sampling frequency of the channel model \( (f_s \geq 1/T) \), and \( v \) the speed of the mobile. The following correlation parameters for two different scenarios were estimated in [4]:

\[ \varepsilon_{SU} = 0.82, \quad D = 100 \text{ m suburban} \]
\[ \varepsilon_{U} = 0.30, \quad D = 10 \text{ m urban}. \]

The time correlation of the shadowing depends on the velocity \( v \) of the mobile. To generate the time varying slow fading coefficients \( \gamma_p \) a Gaussian random process is filtered using the (one-pole) IIR-filter and multiplied by \( \sigma_\gamma \).

**Array propagation:**

The propagation of a plane wave impinging on the antenna array causes a time delay \( \Delta_m(\theta_p) \) at different antenna elements, which results in a phase-shift

\[ a_m(\theta_p) = e^{j\phi_m(\theta_p)} \] (4)

of the incoming wave. These phase shifts can be expressed as

\[ \phi_m(\theta_p) = 2\pi\Delta_m(\theta_p) \frac{c}{\lambda}. \] (5)

The presented channel model considers this propagation delay to be able to simulate spatial wide-band arrays \( (d \gg \lambda) \). For an ULA the propagation delay at antenna \( m \) for path \( p \) is given as:

\[ \Delta_{p,m} = m \frac{d \sin \theta_p}{c}. \] (6)

**Signal \( s_{m,p}(t) \):**

The signal \( s_{m,p} \) received at antenna \( m \) is delayed by the path delay \( \tau_p \) and the propagation delay \( \Delta_{m,p} \). Further the additional phase shift \( a(\theta_p) \) due to antenna propagation is considered. This results in a time and phase shifted pulse shape \( g(t) \). The resulting signal at antenna \( m \) for the \( p \)-th multipath is given as:

\[ s_m(t - \tau_p) = \sum_k d_k a_m(\theta_p)g(t - \tau_p - \Delta_{p,m} - kT), \] (7)

where \( T \) defines the symbol rate. The pulse shaping filter \( g(t) \) is often implemented as a
Nyquist filter such as the Root Raised Cosine (RRC) filter:

\[ g(t) = \sqrt{\frac{E_g}{T} \left( \frac{\cos(\frac{\pi(1+\alpha)t}{T}) + \sin(\frac{\pi(1-\alpha)t}{T})}{(\pi t/T)(1 - (4\alpha t/T)^2)} \right)} . \] (8)

In a discrete time simulation the pulse shaping filters in the transmitter are often implemented as FIR-filters. Since the multipath delays are integrated in the filters, \( P \) pulse-shaping filters for each antenna have to be implemented.

![Diagram of multipath implementation](image)

Fig. 3. Implementation of multipaths as delayed Nyquist pulses for the \( m \)-th antenna

Representing the path and propagation delay within the transmitted pulse shape offers major advantages:
1. No oversampling is needed to represent path delays which are not integer multiples of the sampling time, since the path delays are exactly represented within the time delayed pulse shape \( g(t - \tau_p - \Delta_{p,m}) \).
2. The array propagation is no longer considered only as a phase shift of the incoming plane wave (narrow-band assumption), since the time delay \( \Delta_{p,m} \) between the antennas is directly taken into account.

Therefore, this model also allows simulation of systems, where the spatial narrow-band assumption does not hold (large antenna separation, wide-band signals).

III. MOBILITY MODEL

A crucial subject for the simulation of space-time channels are the moving mobiles. Although mobility is already taken into account for calculation of fading coefficients (see II), no specific movement is considered for changes in \( \tau_p \) and \( \theta_p \). The emerging new paths (with new \( \tau_p \) and \( \theta_p \)) due to mobility influence the multipath structure of the spatial and temporal channel impulse response. The positions of dominant scatterers drawn from GBSB models are more likely to be distributed in the vicinity of the mobile. If the mobile moves away from its location, this is no longer valid. In fact, if a mobile moves in a given direction, no dominant reflector will be close to the mobile after some time, which violates the assumptions used to derive the GSB models. Therefore, it is reasonable to model vanishing ‘old’ paths and emerging ‘new’ ones in order to account for mobility effects more accurately.

Here, we follow a rather pragmatic approach, which takes care of the mobility implications on \( \tau_p \) and \( \theta_p \) in the statistical model while keeping the simulation model as simple as possible:
- A path is discarded, if the corresponding slow fading coefficient \( \gamma_p \) falls below a given threshold \( \Gamma_{min} \).
- A new path is generated from the underlying GSB model for each discarded old multipath.

The channel model will continually replace ‘old’ paths by ‘new’ ones. The parameter \( \Gamma_{min} \) affects the replacement of old path and must be chosen carefully depending on the scenario.

IV. VERIFICATION WITH MEASUREMENTS

Measurements have been analyzed in order to verify the following assumptions of the channel model:
- the channel impulse response consists of discrete multipath components with a distinct AOA and have a limited path duration.
- Each multipath has an independent fast fading.

The measurements were performed in a suburban area with two-story houses. The measurement bandwidth was 120 MHz using an ULA with 8 0.4\( \lambda \)-spaced antenna elements [3].

![CIR measured at the first antenna](image)

Fig. 4. CIR measured at the first antenna over...
a 4 second time interval. The transmitter was moved with about 8 km/h. Besides a strong LOS, three dominant scatterers caused significant multipath components. They were dedicated to houses in the scenario. As the transmitter moved, two of the multipath components occurred or disappeared after some time. This shows the importance of a slow fading and a mobility model for the simulation of space-time algorithms which should cope with these spatial and temporal varying effects.

To verify the channel model assumptions of independent Doppler shifts of the multipath components the delay Doppler spectrum was examined. As shown in Figure 5 each multipath has a different maximum Doppler shift. The correlation between the fading characteristics of the multipath components where low. The average spectra of the sum of all delay taps results in the typical Jakes-spectrum. The results indicate, that the basic channel model assumption of independent fast fading of each multipath component could be confirmed by measurements. Therefore, the new channel model enables a realistic simulation of space-time channels for moving mobiles.

![Average Delay Doppler Spectrum](image)

Fig. 5. Average Delay Doppler Spectrum

Static measurements were used to verify the assumption of distinct AOA’s for each multipath. This is done by analyzing the correlation between the antenna elements. The spatial correlation between the antennas can be expressed using the correlation measure

\[ r(\tau) = \frac{||R_{\tau} - I||_F}{\sqrt{(M-1)M}}. \]  

where \( R_{\tau} \) is defined as the expected value

\[ R_{\tau} = E\left< h^*(\tau)h(\tau) \right> \]  

of the channel impulse response vector

\[ h(\tau) = [h_0(\tau) \ h_1(\tau) \ \cdots \ h_{M-1}(\tau)]^T \]  

with

\[ h_m(\tau) = \sum_{p=1}^{P} \sqrt{P(\tau_p)}a_p(t)a_m(\theta_p)g(\tau - \tau_p - \Delta_{p,m}). \]

\( I \) is the identity matrix and \( || \cdot ||_F \) defines the Frobenius norm. The correlation measure \( r(\tau) \) ranges from 0.0 (antenna outputs are uncorrelated) to 1.0 (antenna outputs are perfectly correlated).

![h0(\tau) and r(\tau) of a measured space-time channel](image)

Fig. 6. \( h_0(\tau) \) and \( r(\tau) \) of a measured space-time channel

![Simulation of a Space-Time-Channel (at 8 antennas)](image)

Fig. 7. \( h_0(\tau) \) and \( r(\tau) \) simulated with the space-time channel model

The lower part of Figure 6 shows the correlation measure for the presented CIR’s. If a strong multipath is present, the correlation \( r(\tau) \) is high. This strong correlation indicates that the wavefront arrives from a distinct AOA, which implies that the signals at the antenna elements are basically phase shifted copies of each other. The value of \( r(\tau) \) for \( \tau' \)'s, where no strong multipath is present, is much lower and is influenced by antenna coupling and other effects, which are not considered in detail here. The measurements
therefore confirm the assumption that the multipath components result from dominant reflectors with distinct AOA’s and small angular spread. If more than one wavefront arrive from different AOA’s simultaneously, the correlation is reduced (see multipath components at \( \tau = 320 \text{ ns} \) and \( \tau = 370 \text{ ns} \) in Figure 6).

The same effects are modeled in the vector channel model when multiple paths are drawn with path delays corresponding to one symbol period. Figure 7 shows an example of CIR’s generated with the channel model. The simulated space-time channel has comparable spatial correlation characteristics for strong multipath components. However, the relatively high level of spatial correlation between significant multi-paths which can be observed for the measured CIR’s is not present in the model itself. These effects can easily be considered by introducing a suitable coupling matrix. Modeling this antenna coupling is an important issue since it reduces the achievable diversity gain in multipath scenarios. With this extension the vector channel model generates spatial correlation characteristics similar to the measured space-time channels.

Finally, the simulated space-time fading is compared with dynamic measurements. The model parameters were chosen to fit measurement scenarios in order to compare the model with measurement results (\( v = 10 \text{m/s} \) \( \tau_{\text{max}} = 200 \text{ns} \)). The simulated space-time fading characteristics (Figure 8) show good conformity with the measured space-time fading characteristics (Figure 9).

Fig. 8. Simulated space-time selective fading

V. CONCLUSIONS

In this paper the implementation of a vector channel model with stochastic fading simulation for space-time processing has been described. The combination of stochastic and geometrical assumptions results in a mathematically tractable and computationally efficient channel model which allows the characterization and simulation of a great variety of vector channels. The implementation of this model allows the simulation of the influence of the array propagation for spatial narrow-band or wide-band (large antenna displacements) antenna arrays. A major advantage of the new approach compared with other models used for space diversity applications is the inherent modeling of the correlation of the antenna outputs as well as fading effects caused by mobility. Therefore, it allows investigations of the actually achievable diversity gains using antenna arrays.

Assumptions of the channel model have been confirmed by measurements. Therefore, a realistic simulation of space-time channels is possible.

The channel model has been implemented as a hierarchical model for the COSSAP-simulation platform. It is going to be included in a forthcoming release of COSSAP.

REFERENCES


