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A New Stochastic Spatio-Temporal Propagation Model (SSTPM) for Mobile Communications with Antenna Arrays

Robert J. Piechocki, *Student Member, IEEE*, Joe P. McGeehan, and George V. Tsoulos, *Member, IEEE*

Abstract—In order to evaluate the performance of third-generation mobile communication systems, radio channel models are required. The models should be capable of handling nonstationary scenarios with dynamic evolution of multipaths. In this context and due to the introduction of advanced antenna systems to exploit the spatial domain, a further expansion is needed in order to include the nonstationary characteristics of the channel. In an attempt to solve these problems, this paper presents a new stochastic spatio-temporal propagation model. The model is a combination of the geometrically-based single reflection and the Gaussian wide-sense stationary uncorrelated scattering models, and is further enhanced in order to be able to handle nonstationary scenarios. The probability density functions of the number of the multipath components, the scatterers' lifetime, and the angle of arrival are calculated to support these features. The input parameters of the model are based on results from measurement campaigns published in the open literature.

Index Terms—Antenna arrays, radio channel model, wireless communications.

I. INTRODUCTION

THE propagation models that have been developed to date to simulate the radio channel have evolved according to the needs of the mobile communication industry. As a result, propagation models for first-generation analog systems considered the power and Doppler characteristics of the radio signal. Second-generation systems utilize wideband digital modulation and this required an extension in order to include the temporal characteristics of the radio channel. Hence, models for second-generation systems provide Doppler characteristics along with power delay profiles. It is almost certain, mainly due to strict frequency efficiency requirements, that emerging third-generation systems will have to exploit more efficiently the spatial domain. Consequently, there is currently a demand for new models that will provide the required spatial and temporal information necessary for studying such systems.

Spatio-temporal models can be generally classified into two groups: deterministic and stochastic. With deterministic models the channel-impulse response (CIR) is obtained by tracing the reflected, diffracted, and scattered rays, with the help of databases that provide information about the size and location of physical structures in addition to the electromagnetic properties of their materials [1]–[4]. Deterministic models have the advantage of providing the ability to generate accurate site specific and easily reproducible information. Stochastic models on the other hand describe characteristics of the radio channel by means of joint probability density functions (pdfs). Statistical parameters employed in such models are usually estimated from extensive measurement campaigns or inferred from geometrical assumptions. Stochastic models usually need less information than deterministic models, and they produce more general results given that many repetitions are performed.

This paper is structured as follows. Section II presents the proposed radio channel model and describes the employed parameters. It also derives expressions and discusses issues such as the Doppler spreading, the angle of arrival, the number of multipath components, and the multipath components' lifetime. Section III discusses the range of values for the parameters employed by the model in order to achieve more accurate modeling of different radio channel types. This information is based on results from extensive measurement campaigns, published in the open literature. Typical results generated by the model are presented in Section IV, and finally Section V presents a number of conclusions drawn from this paper.

II. DESCRIPTION OF THE MODEL

A. General Description

The model is a combination of two statistical channel models, the geometrically-based single reflection (GBSR) [5]–[7] and Gaussian wide-sense stationary uncorrelated scattering (GWSSUS) [8] channel models, and is extended to include temporal variations. Since it is geometrically based, the signal statistics depend on the position of the base station (BS), the mobile station (MS), the geometrical distribution of the scatterers, and the velocity of the mobile. In order to simplify the derivation of expressions for the radio channel characteristics, two important assumptions are made within the GBSR channel model. Firstly, that the signal undergoes only one reflection as it travels from the MS to the BS, and secondly, that all the scatterers are confined within a scattering disc. With a GWSSUS model the scatterers are grouped into N clusters under the assumption that there is insignificant time
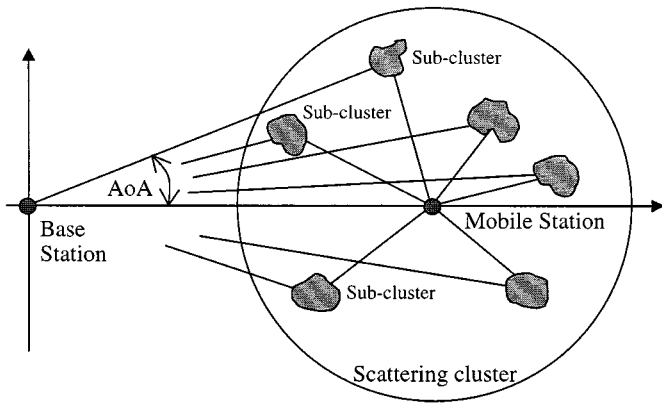
Fig. 1.   Combination of the GBSR and GWSSUS channel models.

dispersion in each of these clusters. The steering vector **s** due to multipaths from the kth cluster can be expressed in this case as the sum of all the contributions (L) from the scatterers within the kth cluster [8]

$$\mathbf{s}_k = \sum_{i=1}^{L} \alpha_{i,k} \exp(-j\xi_{i,k})\mathbf{a}(\varphi_k, f). \tag{1}$$

For the kth cluster, $\alpha_{i,k}$ represents the amplitude and $\xi_{i,k}$ the phase of the multipath resulting from the ith scatterer and $\mathbf{a}(\varphi_k, f)$ is the vector of the complex responses of the receive antenna elements for the direction φ_k and at frequency f. In general, the steering vector **s** depends also on the elevation angle, but for the sake of simplicity, (1) assumes azimuth dependency only. By the central limit theorem it can be shown that the steering vectors $\mathbf{s}_k$ are complex Gaussian distributed random variables. It is assumed that the locations of the N clusters remain unchanged over several data bursts. The GWSSUS channel does not impose any conditions on the spatial distribution of the received power, and hence, it requires additional information if it is to be used in space–time analysis. Contrary to the GWSSUS model, the GBSR model provides space–time characteristics. The scatterers in this case are assumed to be isotropic reradiating elements with random complex scattering coefficients, (yet in practice it is rather difficult to assign realistic scattering coefficients [9]). Nevertheless, GBSR channel models do not provide information about the temporal evolution of the generated CIR, e.g., there is no relationship between consecutive snapshots. Hence, the only way to employ these models is to assume that consecutive CIRs are uncorrelated, which is a rather unrealistic assumption.

In order to relax the problems associated with both channel models, it is proposed in this paper to combine them by replacing the single scattering elements in the GBSR model with subclusters containing scattering elements that satisfy the GWSSUS channel assumptions (see Fig. 1). To further enhance the flexibility of the model, time variations associated with the movement of the mobile are also considered.

Given that the transmitting source (mobile) is in the far field of the BS antenna, then the received signal at the BS is a superposition of plane waves. In the model's basic case, the signal reaches the BS after it has been reflected from the scatters in the vicinity of the mobile. As mentioned above, each scatterer now constitutes a subcluster, which includes a number of scatterers. The subclusters satisfy narrow-band assumptions, i.e., the delay
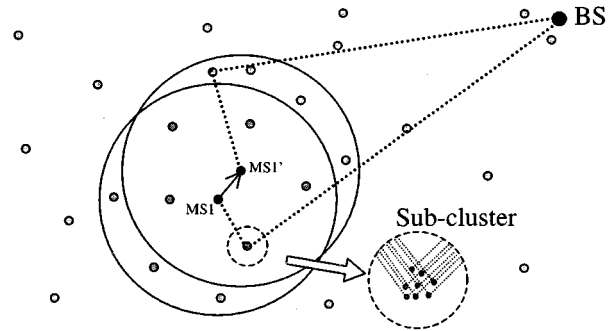

Fig. 2.   Principle for the extension of the combined GBSR-GWSSUS model to include temporal variations.
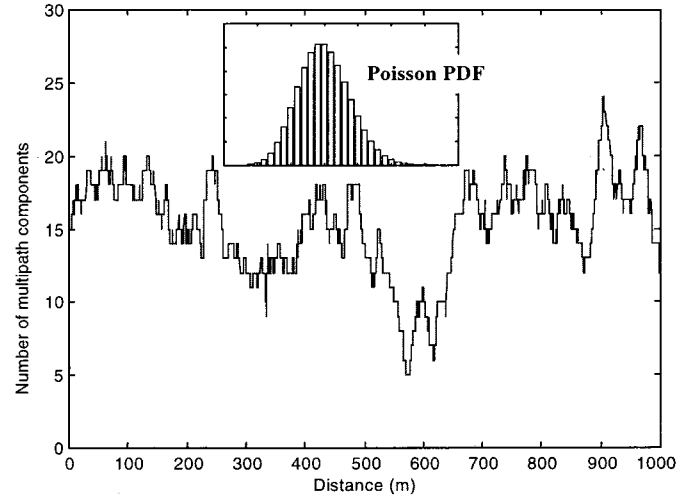

Fig. 3.   Example of the fluctuation of the number of multipath components in macrocellular urban environment with resulting Poisson pdf, according to the SSTPM model.

and angle spread are very small when compared with the time and space resolution of the employed system. For simplicity, the subclusters are also referred to as scatterers in the remainder of the paper, unless otherwise stated.

Clearly, a basic problem for this kind of model is to define the shape and size of a cluster. A straightforward solution is to use a circular shape with a given radius R [10]. When site specific information (databases) is not available, one can assume a uniform distribution of scatterers with a given area density (number of scatterers per square kilometer). The area density of the scatterers will obviously depend on the different types of environment, as discussed in detail later in the paper.

Fig. 2 shows the principle for the extension of the combined GBSR and GWSSUS models to include nonstationary scenarios. The mobile is located at the centre of the circular scattering area (the cluster), and as it moves, so too does the cluster. The scatterers remain at fixed locations and although they are uniformly placed over a larger area (e.g., the whole cell), the active scatterers only include those covered by the cluster. When the mobile moves, a number of new scatterers contribute to the received signal (move into the cluster) and at the same time, some scatterers move out of the cluster, or their multipath contributions fall below some predetermined power window. For the algorithm employed here, there is no fixed number of scatterers for a simulation run. The number of multipath components fluctuates with time (or distance covered by the MS)—as depicted in Fig. 3. The number of
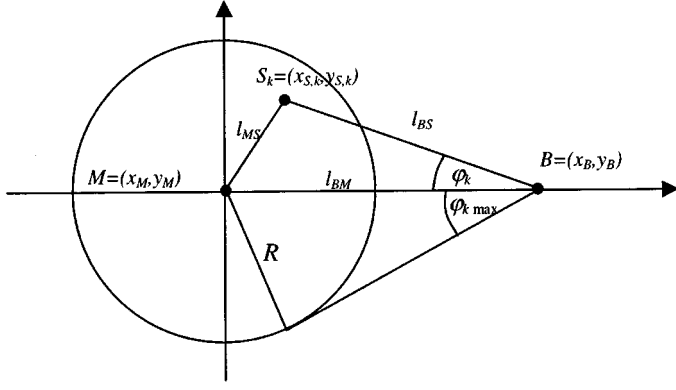
Fig. 4. The geometry of the model.

scatterers at a particular time instant is governed by a Poisson process with a given mean—see Fig. 3 (a proof is provided in Appendix A). In essence, this process is similar to many other random processes. For example, in biology, the number of particular bacteria in a given volume; in physics, the radioactive decay of a number of emitted alpha particles per time unit and so on. The expected number of scatterers depends on the area density of the scatterers and the cluster size, hence it changes for different types of environment (Section III discusses this issue in greater detail).

The model assumes a constant velocity for the mobile motion. This is sufficient to introduce nonstationarity into the channel model. The instantaneous Doppler spectra also change on a snapshot by snapshot basis. This is caused by the angular change between the scatterers, the mobile, and the direction of the mobile motion.

B. Geometrical Relations

Fig. 4 illustrates the geometry of the model. All scatterers (S_k), the MS (M), and the BS (B) are placed in the same plane at locations $S_k = (x_{S,k}, y_{S,k})$, $M = (x_M, y_M)$, $B = (x_B, y_B)$. The distance between the kth scatterer and the mobile is given by $l_{MS} = \|M - S_k\|$. The value of l_{MB} and l_{BS} can be calculated in a similar manner.

The angle of arrival of the kth multipath component is

$$\tan(\varphi_k) = \frac{y_{S,k} - y_B}{x_B - x_{S,k}}. \tag{2}$$

The path length and the time of arrival of the ray resulting from the kth scatterer are given by

$$l_k = \|M - S_k\| + \|B - S_k\| = l_{MS,k} + l_{BS,k} \tag{3}$$
$$\text{ToA}_k = \frac{l_k}{c} \tag{4}$$

where c represents the speed of light. The kth multipath due to the kth scatterer can be expressed as

$$Y_k = \left(\frac{1}{l_k}\right)^{n/2} \exp\left(-j2\pi\frac{l_k}{\lambda}\right) \cdot \mathbf{s}_k \tag{5}$$

where n is the pathloss exponent, λ is the wavelength, and $\mathbf{s}_k$ is the steering vector given by (1).

The instantaneous Doppler shift of each multipath component can be calculated from

$$f_{\text{Dop},k} = \left[\frac{-1}{\lambda}\right]\left[\frac{dl_k(t)}{dt}\right]. \tag{6}$$

Based on (6), the discrete Doppler spectrum (assuming CW transmission) centred at $f_c = 0$ Hz is

$$S_{\text{Dop}}(f) = \sum_{k=1}^{N} Y_k \delta\left(f - \left(\left(\frac{V}{\lambda}\right)\left(\frac{-\Delta l_k}{\Delta d}\right)\right)\right) \tag{7}$$

where $\delta(\cdot)$ is the Dirac function, Δd the distance covered by the MS within a single time step Δt at constant velocity V, and Δl_k is a corresponding change of length of the kth path.

The angular spread of the channel can be described by the pdf of the angle of arrival, which was calculated for such a model in [11] and shown to be

$$f_\varphi(\varphi_k) = \begin{cases} \dfrac{2}{\pi}\cos(\varphi_k)\sqrt{\cos^2(\varphi_k) + F^2 - 1}, \\ \quad \text{for } -\varphi_{k\,\max} < \varphi_k < \varphi_{k\,\max} \\ 0, \quad \text{elsewhere} \end{cases} \tag{8}$$

where $F = R/l_{BM}$, i.e., the cluster radius over the distance between the MS and the BS. The formula given in (8) is a special case of the elliptical case derived in [11]. The elliptical cluster model is more flexible as a static GBSR model. However, in order to avoid the additional complexity associated with the elliptical cluster, only the circular scattering cluster is adopted here. For the proposed dynamic mode, the elliptical scattering cluster would also need to support the direction of the ellipse's semiaxes versus the direction of motion.

C. Multipath Components' Lifetime

As the mobile travels, some scatterers move out of the chosen disc of scatterers while others move in and as a result new multipath rays contribute to the received signal ("*multipath generation*"). Furthermore, multipath rays exist for a period of time t_l and then disappear ("*multipath recombination*"). Clearly, the duration t_l is a random variable described by some pdf and it also depends upon the velocity V of the mobile and the scattering disc radius R.

The pdf of the scatterers' lifetime is given by (15) and is depicted in Fig. 5 (a proof is provided in Appendix B). It can be seen from (15) and Fig. 5 that the pdf of the time duration approaches infinity for $t_l = 2R/V$, i.e., when the diameter of the scattering cluster aligns with a trace of a scatterer. Nevertheless, this is not a problem, since the pdf is continuous and the probability of such an event is zero.

D. Simulation Procedure

Typically, simulating the mobile radio channel with statistical models involves generating the required parameters (e.g., angle of arrival, time of arrival, amplitude, phase), according to provided joint pdf functions. This procedure is feasible with time-invariant GBSR models [5]. However, the proposed model also provides the Doppler shift and time evolution of the parameters. As a result the accuracy and complexity of the model is increased. The simulation procedure can no longer be based on
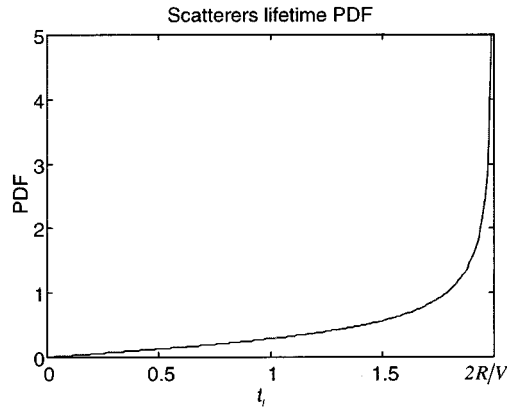
Fig. 5.   The pdf of the multipath components' lifetime.

joint pdf functions, as it would result in prohibitively complex formulas.

The simulation procedure can be summarized as follows.

1) Choose input parameters based on Table I. Additionally choose MS velocity V, and the number of snapshots to be provided by the model—N_S. The sampling instant should be set to a fraction of the carrier wavelength (e.g., $\Delta d = \lambda/16$).

2) Generate the direction of the velocity vector $\bar{V}$ (uniform angle). Generate the positions of the scatterers with an area density σ (Table I) in some larger area Ω (Ω must include the scattering cluster for all time instants). Since each scatterer constitutes a subcluster (see Fig. 2), we must generate a further L (Table I) subscatterers in the circular subcluster with radius R_s (Table I) centred on each scatterer.

3) Calculate the required parameters according to (2), (4), (5), and (7).

4) Move the scattering cluster by $\bar{V} * \Delta d$, test for new scatterers, and remove those that are now outside the cluster.

5) Repeat points 3) and 4) for all required snapshots N_S.

Although (7) provides an explicit value for the Doppler shift, this is not necessary for the simulations. This occurs because the complex amplitude in (5) changes on a snapshot-by-snapshot basis and it already contains the impact of the Doppler phenomena. This also simplifies the entire radio channel simulator, since there is no need for an additional Doppler filter block.

III. MODELLING THE DIFFERENT ENVIRONMENTS

Different propagation scenarios have different impacts on the CIR, and this must be taken into account if a realistic model is to be constructed. The mobile radio propagation channel can be categorised based on the size of the cells and the height of the BS antennas into macro, micro, and picocells [10]. The presented model is intended to simulate macro and microcellular environments. Simulating picocells with geometrically-based statistical models requires a slightly different approach, as discussed in [5].

Microcells have typical cell radii in the order of hundreds of meters, with BS antenna heights generally below the surrounding rooftops. They are employed in urban areas, especially

in city centres, in order to solve capacity problems. Macrocells on the other hand, can have radii of the order of several kilometers and the BS antennas are normally mounted above rooftops. Macrocells can be found in a large variety of environments, and this allows for a further degree of classification based on environmental characteristics. Macrocells can be broken down into urban, suburban, and rural cells. A brief description of the basic characteristics of such environments is provided in the following section (based on [13]–[16]).

1) Macrocell Urban: The BS is positioned above rooftops, the MS is surrounded by a dense irregular scattering structure with multistory buildings. The line-of-sight (LOS) is usually blocked and the area of contributing scatterers is confined to a few hundred meters. The expected area density σ of the scatterers lies between $70 < \sigma < 600$ (scat/km^2).[1]

2) Macrocell Bad Urban: This cell type differs from the macrocell urban type by an additional scattering cluster, which is uniformly distributed within the cell range [8].

3) Macrocell Suburban: As for the urban channel, the BS antenna is positioned above the rooftops. The MS is surrounded by a scattering structure that includes a small number of scatterers, generally of lower density. Due to the open environment, waves from more distant scatterers may reach the BS antenna. The LOS path is usually available and the density of high buildings is lower compared to the urban case. The expected area density of the scatterers lies between $10 < \sigma < 35$ (scat/km^2).

4) Macrocell Rural: The scattering environment is open and sparse, with a low density of short buildings. A direct path is usually available and there are a few distant scatterers (e.g., due to hills). The expected area density of the scatterers lies between $3 < \sigma < 7$ (scat/km^2).

5) Microcell Urban: In microcells, the BS antennas are usually located below the rooftop level and as a result this demands for scatterers local to the BS to be taken into account. The direct path may or may not be available and the diameter of the local scattering cluster is in the order of the cell radius. The expected area density of the scatterers lies between $7000 < \sigma < 60\,000$ (scat/km^2).

All the above parameters, together with the detailed information required to simulate the described channel types, are summarized in Table I. For each channel type, the radius R of the local scattering cluster (around the MS) is defined together with the mean number of scatterers N. Then the two numbers can be used to give the scatterer area density. As indicated in Table I, for some channel types the LOS with a predefined Rician K-factor can be chosen. However, the availability of the LOS should not be taken for granted, nor should it be rejected as a prerequisite. Usually, a good approach is to test a system separately in both scenarios, i.e., with and without the LOS.

IV. NUMERICAL EXAMPLES

This section presents examples for characteristics of the mobile radio channel, as generated by the SSTPM model described

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[1]Although the area density of the scatterers is not explicitly stated in the provided references, it can be easily obtained from the information provided for the number of scatterers in a given disc with known area.

TABLE I
SUMMARY OF PARAMETERS USED WITH THE SSTPM MODEL TO SIMULATE DIFFERENT OPERATIONAL ENVIRONMENTS

PROPERTY	VALUE
Macrocell Urban	**scatterers density area: $70 < \sigma < 600$ [scat/km^2]**
Total mean number of scatterers	$N_{tot}=20$
Mean number of local scatterers	$N=20$
Radius of local scatterers	$100\ \text{m} \leq R \leq 300\text{m}$
Cell range	$3000\lambda \leq CR \leq$ maximum system radius
Macrocell Bad Urban	**scatterers density area: $70 < \sigma < 600$ [scat/km^2]**
Total mean number of scatterers	$N_{tot}=30$
Additional scattering clutter	1 clutter
Number N_a of scatterers in the additional clutter	$N_a=N/2$
Radius of additional clutter	$R_a=R/2$
Distribution of the additional clutter	uniform within cell range
Further parameters	as for "Macrocell Urban" type
Macrocell Sub-urban	**scatterers density area: $10 < \sigma < 35$ [scat/km^2]**
Total mean number of scatterers	$N_{tot}=10$
Mean number N of local scatterers	$N=8$
Radius of local scattering cluster	$300\ \text{m} \leq R \leq 500\text{m}$
Number N_R of additional distinct remote scatterers	uniform between $0 \leq N_R \leq 4$
Distribution of the additional distinct remote scatterers	uniform within cell range
Power in LoS component	$K_{Rice}= 0 - 20\ \text{dB}$
Further parameters	as for "Macrocell Urban" type
Macrocell Rural	**scatterers density area: $3 < \sigma < 7$ [scat/km^2]**
Total mean number of scatterers	$N_{tot}=6$
Mean number N of local scatterers	$N=4$
Radius of local Scatterers	$500\ \text{m} \leq R \leq 800\text{m}$
Number N_R of additional distinct remote scatterers	uniform between $0 \leq N_R \leq 4$
Distribution of the additional distinct remote scatterers	uniform within cell range
Power in LoS component	$K_{Rice}= 0 - 40\ \text{dB}$
Further parameters	as for "Macrocell Urban" type
Microcell Urban	**scatterers density area: $7000 < \sigma < 60000$ [scat/km^2]**
Total mean number of scatterers	$N_{tot}=20$
Mean number N of local scatterers	$N=18$
Radius of local Scatterers	$10\ \text{m} \leq R \leq 30\text{m}$
Cell range CR	$30\text{m} \leq CR \leq 500\text{m}$
Number N_{BS} of local to BS scatterers	uniform between $0 \leq N_{BS} \leq 4$
Distribution of local to BS scatterers	range – uniform between [0 10m] angle – uniform in cell sector width
Power in LoS component	$K_{Rice}= 0 - 20\ \text{dB}$
Common parameters	
Reflection coefficient ρ for scatterers in the sub-clusters	uniform phase between [0 2π] uniform amplitude between [0 1]
Number of scatterers in the sub-clutter	$L=8$
Radius of the sub-clutter	$Rs=10\lambda$

in Section III. It is assumed that a narrow-band signal is transmitted at a frequency $f = 1.8$ GHz and that the BS antenna is a linear array consisting of omnidirectional elements.

A typical Rayleigh (for channels without LOS) fading envelope at a frequency f, as seen by one antenna element at the BS, is depicted in Fig. 6. The received signal is spread across the full Doppler range $(-f_{Dopmax} < f < +f_{Dopmax})$ and is independent of the scattering cluster size, hence the number of fades per second is the same for all channel types. It can be seen from the same figure that the number of fades per second of the modulus of the steering vectors is lower. This occurs because of the minor angle spreading in the subclusters. The number of fades per second of the steering vectors depends upon the distance to the MS. The closer the subcluster is to the mobile, the larger the number of fades of the steering vector. Fig. 7 shows results generated by the SSTPM model for a macrocellular bad urban scenario. It can be seen from the figures that apart from the multipaths due to scatterers local to the mobile, there are multipaths due to distant scatterers as well as multipaths reflected on the additional cluster. All of them are distinguished both in space and time [Figs. 7(a) and (b)]. Fig. 7(c) depicts the discrete Doppler spectrum given by (7), and Fig. 7(d) shows a plot of the correlation coefficient between the real parts of the received complex envelope as a function of the interelement distance.

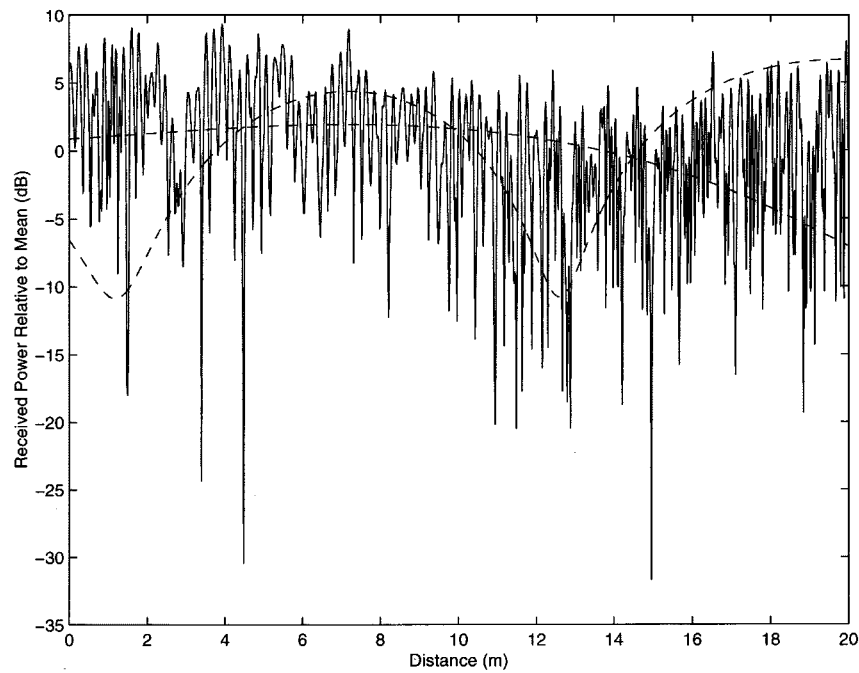Fig. 6.   Typical fading of the superposition of all multipaths: solid line; two typical fluctuations of the steering vectors' modulus: two dashed lines.
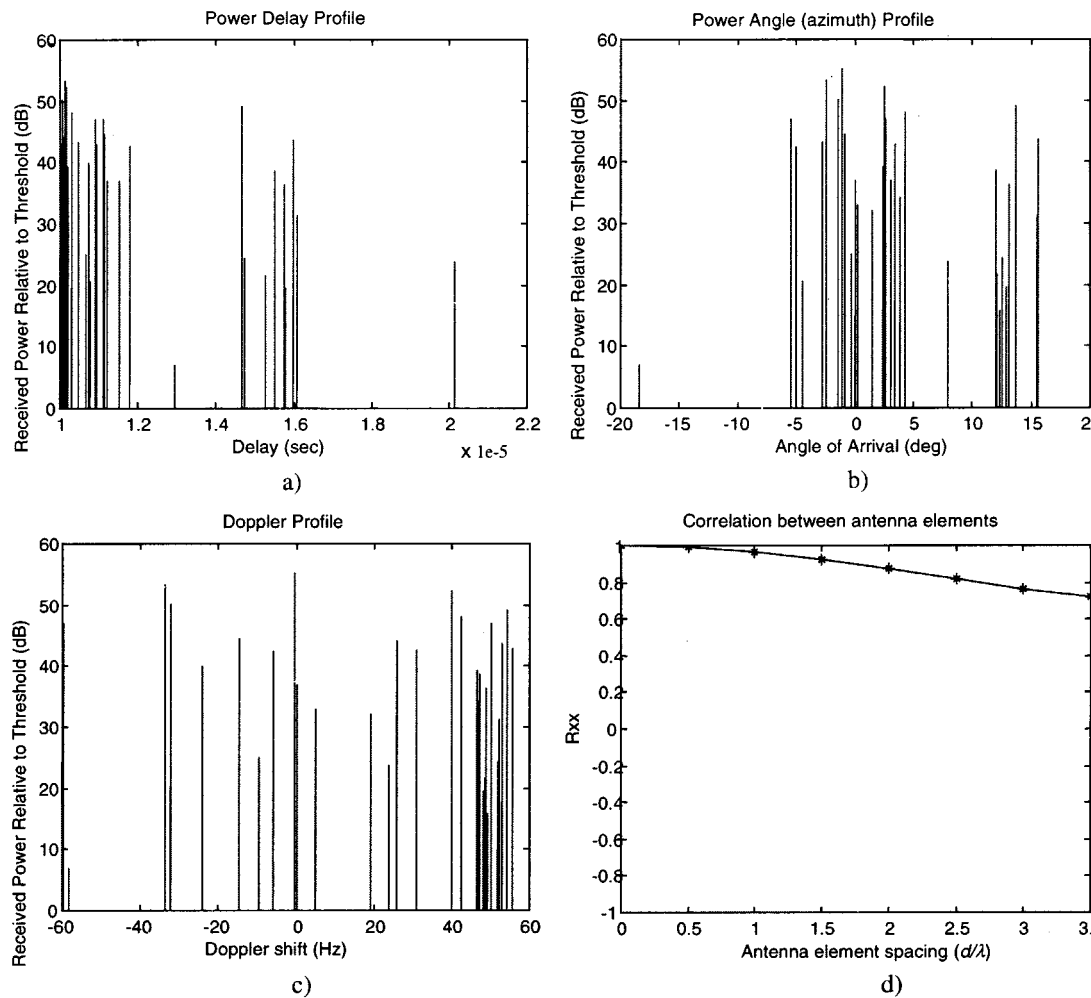

Fig. 7.   Typical results generated by the model for a macrocellular bad urban scenario in the uplink (power normalized to the weakest ray): (a) power-delay profile; (b) power-angle (azimuth) profile; (c) Doppler profile; (d) correlation between antenna elements.

V. CONCLUSIONS

The SSTPM proposed in this paper alleviates problems encountered in known statistical channel models. A hybrid approach that combines two classes of radio channel models, the GBSR and the GWSSUS, has been proposed in order to simultaneously exploit the advantages and minimize the disadvantages of both classes of models. An extension to the proposed hybrid model includes the generation of consecutive snapshots based on the method of a moving scattering cluster. This extension introduces temporal characteristics to consecutive CIRs and hence makes them correlated. This is more representative of reality than the previous uncorrelated assumption made by the GBSR and GWSSUS models. This also allows for direct calculation of the correlation functions, since complex envelopes are available. A further extension in the proposed model allows the number of multipaths to be varied as the MS moves. The number of multipaths follows a random process with Poisson distributed values. The pdf of the "scatterers' lifetime" has been calculated and shown to depend upon the size of the scattering cluster and the MS velocity. The Doppler spreading and the pdf of the angle of arrival were also provided. To further increase the model's ability to provide realistic channel information, parameters for five different types of environments, ranging from microcellular urban to macrocellular rural, are incorporated into the model. The values of these parameters provide environment-specific characteristics and are based on results published in the open literature from extensive measurement campaigns.

APPENDIX A
PDF OF A NUMBER OF SCATTERERS

Let the scattering cluster area be denoted by A and some larger area by Ω, with $A \subset \Omega$ (Ω-might be the cell). If the scatter area density σ is uniform across Ω, the probability for one scatterer to be inside A is $p = A/\Omega$. If n is the number of scatterers in Ω, then the average number of scatterers in A is $N = p \cdot n = A \cdot \sigma$. The probability for exactly k scatterers to be in A is given by a binomial law

$$\binom{n}{k} p^k (1-p)^{n-k} \cong \frac{1}{k!} N^k \left(1 - \frac{N}{n}\right)^{n-k} \qquad (9)$$

where $n(n-1)\ldots(n-k+1) \cong n^k$. For a very large number of scatterers, the limit of the binomial coefficient is

$$P(k) = \lim_{n \to \infty} \frac{1}{k!} N^k \left(1 - \frac{N}{n}\right)^{n-k} = \frac{N^k}{k!} e^{-N} = \frac{(A\sigma)^k}{k!} e^{-(A\sigma)} \qquad (10)$$

Hence, the probability distribution function of the number of scatterers in the scattering cluster with area A is given by the Poisson distribution.

APPENDIX B
PDF OF MULTIPATH COMPONENTS' LIFETIME

In the case of a uniform distribution of scatterers, the traces y of all the scatterers contributing to the received signal cross the disc diameter at a distance x from the centre of the disc. The variable x has a uniform distribution since the marginal distribution across a line containing the diameter is uniform, hence

$$f_x(x) = \frac{1}{2R}, \qquad -R \le x \le R. \qquad (11)$$

The transformation between variables x and y is given by a simple relationship: $y = g(x) = 2\sqrt{R^2 - x^2}$. Now it is possible to find the pdf $f_y(y)$ from (11) and the function $g(x)$. These types of problems are solved by [12]

$$f_y(y) = \sum_{i=1}^{m} f_x(w_i(y)) |J_i| \qquad (12)$$

where $J = dx/dy = w'(y)$ is the Jacobian of the transformation, and $x = w(y)$, is the reciprocal of the function $g(x)$. If $y < 0$, then the equation $y = g(x)$ has no real solutions and thus $f_y(y) = 0$. However, for $y \ge 0$, two solutions exist: $w_1(y) = \sqrt{R^2 - (y/2)^2} = -w_2(y)$. The Jacobians are

$$\frac{dx_1}{dy} = -\frac{dx_2}{dy} = \frac{-y}{4\sqrt{R^2 - \left(\frac{y}{2}\right)^2}}. \qquad (13)$$

Hence the desired pdf is

$$f_y(y) = \frac{y}{4\sqrt{R^2 - \left(\frac{y}{2}\right)^2}} [f_x(w_1(y)) + f_x(w_2(y))]. \qquad (14)$$

From (11) it can be seen that $f_x(w_1(y)) = f_x(w_2(y)) = 1/(2R)$, and also since $y = Vt_l$, then the pdf of the time duration t_l for any given radius R and the mobile velocity V can be calculated as

$$f_t(t_l) = \begin{cases} \dfrac{t_l V}{4R\sqrt{R^2 - \left(\frac{t_l V}{2}\right)^2}}, & 0 \le t_l \le 2\frac{R}{V} \\ 0, & \text{otherwise.} \end{cases} \qquad (15)$$

The mean of the multipath components' lifetime can be simply expressed as

$$E[t] = \int_{-\infty}^{\infty} t_l f_t(t_l)\, dt = \frac{\pi R}{2V}. \qquad (16)$$

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Joe P. McGeehan received the B.Eng. and Ph.D. degrees in electrical and electronic engineering from the University of Liverpool, Liverpool, U.K., in 1967 and 1971, respectively.

He held the position of Senior Scientist at the Allan Clark Research Centre, The Plessey Company Ltd.. Here, he was responsible for the research and development of two- and three-terminal GaAs devices and their application to radar, telecommunications, and ultra-fast logic ($>$5 Gb/s). In September 1972, he joined the academic staff of the School of Electrical Engineering, University of Bath, where he began research into mobile communications in 1974. At Bath, he pioneered research into what he later termed linear modulation for the spectrum efficient transmission of speech and data (64 kb/s in a 5-kHz channel), ray-tracing for propagation prediction in micro, macro, and large cells, automatic gain control, and frequency tracking systems for operation in the fading environment. In 1981, he developed, with his group, what is considered to be the first basic form of what he termed the "software radio," a linear modulation radio based on TTIB using the Intel 2920 digital signal processor.

On appointment to the Chair of Communications Engineering at the University of Bristol in 1985, he successfully developed, with colleagues, techniques for linearizing both narrow-band and broad-band power amplifiers. He continued research into linear modulation techniques and systems, ray-tracing, and initiated research into the use of adaptive beam-forming techniques in cellular and AWA systems. He also established in 1987 and is Director of the Centre for Communications Research at Bristol, which now has some 140 researchers in the fields of wireless communications, optical communications, computational electromagnetics, networks and protocols, and video and image processing. Many aspects of his research have formed the basis of international standards or equipments for the cellular, PCS, or private mobile radio markets. He is currently Managing Director of Toshiba Research Europe Ltd.;Telecommunications Research Laboratory, and Dean of Engineering at the University of Bristol.

Dr. McGeehan is a Fellow of the Royal Academy of Engineering and a Fellow of the Institute of Electrical Engineers. He has served on numerous international committees and standards bodies and was advisor to the UK's first DTI/MOD "Defence Spectrum Review Committee" in the late 70s. He was the joint recipient of the IEEE Transactions Neal Shepherd Memorial Award (for work on SMART Antennas) and the IEE Proceedings Mountbatten Premium (for work on satellite tracking and frequency control systems).

Robert J. Piechocki (S'98) received the M.Sc. degree (with first-class honors) in electrical engineering from the Technical University of Wroclaw, Wroclaw, Poland, in 1997. Since then, he has been working toward the Ph.D. degree at the Centre for Communications Research, University of Bristol, Bristol, U.K.

His research interests include the areas of statistical signal processing for communications and radio channel modeling for wireless systems. He is currently involved in design and optimization of the smart antenna systems for WCDMA.

George V. Tsoulos (M'94) received the Ph.D. degree from the University of Bristol, Bristol, U.K., in 1996, and the M.Eng. degree in electrical and computer engineering from the National Technical University of Athens, Athens, Greece, in 1992.

While at the Centre for Communications Research of the University of Bristol, he was actively involved in all three pioneering European collaborative research projects on adaptive antennas (RACE TSUNAMI I, ACTS TSUNAMI II, and SUNBEAM). In 1998, he became a Research Fellow at the University of Bristol, where his work focused on the area of smart antenna techniques for third-generation mobile communications. He has authored more than 50 international publications and more than 20 technical reports on adaptive antenna related topics. He is member of the organizing committee of the European action COST 260 on smart antennas, expert member of the COST action 259, the Technical Chamber of Greece. He joined the Wireless Technology Practice of the PA Consulting Group, Cambridge, U.K., in 1999. His current interests include design, optimization, implementation, and planning of "intelligent" wireless and broad-band future-generation communication systems.