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A MACROCELLULAR RADIO CHANNEL MODEL FOR SMART ANTENNA TRACKING ALGORITHMS

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Abstract - In order to evaluate the performance of third generation wideband mobile communication systems, radio channel models capable of handling non-stationary scenarios with dynamic evolution of multipaths are required, since stationary models with fixed number of paths and delay information will produce over-optimistic results. 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 also include the non-stationary spatial 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 (GBSR) and the Gaussian Wide Sense Stationary Uncorrelated Scattering (GWSSUS) models, and is further enhanced in order to be able to handle non-stationary scenarios. The probability density functions of the number of multipath components, the scatterers' lifetime and the angle of arrival are calculated for this reason.

I. INTRODUCTION

The propagation models that have been developed until today to simulate the radio channel have evolved according to the needs of mobile communication systems. As a result, propagation models for first generation analogue systems considered the power and Doppler characteristics of the radio signal. Second generation systems utilise 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 is obtained by tracing the reflected, diffracted, scattered and transmitted through walls rays, with the help of databases which provide information about the size and location of physical structures and furthermore the electromagnetic properties of their materials. Deterministic models have the advantage of the ability to provide 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. Statistical parameters employed in such models are usually estimated from extensive measurement campaigns or inferred from geometrical assumptions. Stochastic models usually need less parameters than the deterministic models, and they produce more general results given that many repetitions are performed.

II. DESCRIPTION OF THE MODEL

The underlying concept behind the proposed radio channel model is graphically depicted in Figure 1. The model is a combination of two statistical channel models, the GWSSUS [1] and GBSR [2,3] channel models, and is extended to include temporal variations. Since it is geometrically based, the signal statistics depend on the positions of the basestation, the mobile, the geometrical distribution of the scatterers and the velocity of the mobile. In order to make the derivation of expressions for the radio channel characteristics easier, two important assumptions are made by the GBSR channel models: First, that the signal undergoes only one reflection when it travels from the mobile station to the base station and then, 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 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 (K) from the scatterers within the kth cluster.

$$\mathbf{s}_k = \sum_{i=1}^{K} \alpha_{i,k} \exp\left(-j\xi_{i,k}\right) \mathbf{a}(\varphi_k, f) \qquad (1)$$

Where: α_i is the amplitude and ξ_i the phase of the multipath due to the ith scatterer and $\mathbf{a}(\varphi_k, f)$ is the vector complex response of the receive antenna elements for the direction φ_k and at frequency f. In general, the steering vector $\mathbf{s}$ also depends on the elevation angle, but for simplicity reasons and since this is not something which affects the results of the propagation model, (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.
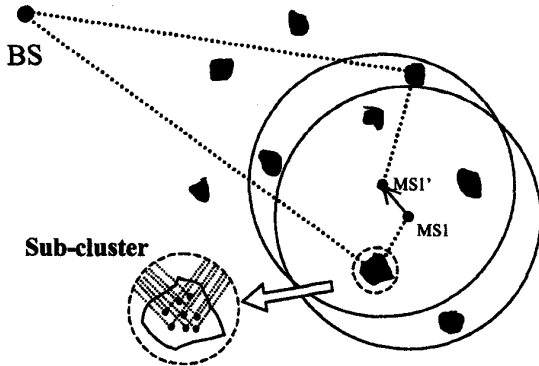

Figure 1: Principle for the extension of the combined GBSR-GWSSUS model to include temporal variations.

The GWSSUS channel model is a single input – single output model and it doesn't impose any conditions on the spatial distribution of the received power. An attempt has been made in [4] to extend GWSSUS to be used in space-time analysis - Directional Gaussian Scattering DGS-GWSSUS. However, since DGS-GWSSUS is entirely measurement based, it requires mass of information to be used. Contrary to the GWSSUS model, the GBSR model provides space – time characteristics. The scatterers in this case are assumed to be isotropic re-radiating elements with random complex scattering coefficients, (yet in practice it is rather difficult to assign realistic scattering coefficients). Nevertheless, the GBSR channel models don't provide information about the temporal evolution of the generated Channel Impulse Response (CIR), e.g. there is no relation between consecutive snapshots. Hence, the only way to employ these models, is to assume that consecutive CIRs are un-correlated, which is an assumption far from reality.

In order to relax problems associated with both propagation models, it is proposed in this paper to combine them by replacing the single scattering elements in the GBSR model with sub-clusters containing scattering elements that satisfy the GWSSUS channel assumptions -Figure 1. In order to further enhance the

flexibility of the model, time variations associated with the movement of the mobile are also considered. Although the proposed model is based on GWSSUS assumptions it produces non-stationary outputs, since in general, second order moments of the received signal change over time.

Generation algorithm

As mentioned above, each scatterer now constitutes a sub-cluster which includes a number of scatterers. The sub-clusters satisfy narrowband assumptions, i.e. the delay and angle spread are very small when compared with the time and space resolution of the employed system. For simplicity the sub-clusters will be also called scatterers in the remainder of the paper, unless otherwise stated.

Figure 1 shows the principle for the extension of the combined GBSR and GWSSUS models to include non-stationary scenarios. The mobile is located at the centre of the circular scattering area, (the cluster), and as it moves, so does the cluster. The scatterers remain at fixed locations and although they are uniformly placed throughout a bigger area (e.g. the whole cell), active scatterers are only those covered by the cluster. When the mobile moves, some new scatterers start to contribute to the received signal (get into the cluster) and at the same time, some scatterers get out of the cluster or their multipath contributions fall below some power window.
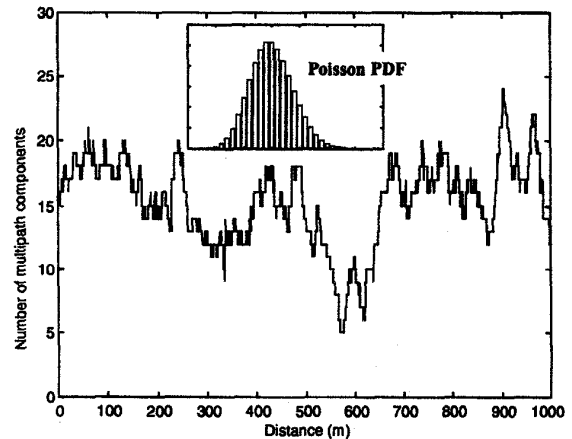

Figure 2: Example for the fluctuation of the number of multipath components in macrocellular urban environment, according to the SSTPM model

For the algorithm employed by the model 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 Figure 2. The number of scatterers at a particular time instant is governed by a random process with Poisson distributed values (a proof is provided in Appendix). In essence, this

process is similar to many other random processes, e.g. 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; or the number of calls arriving within a certain time window in telephony. The expected number of scatterers depends obviously on the area density of the scatterers and the cluster size, hence it changes for different types of environment.

Geometrical relations

According to the assumptions of the GBSR model, all scatterers, the mobile station and the base station are placed in the same plane at locations $S_k=(x_{S,k}, y_{S,k})$, $M=(x_M, y_M)$, $B=(x_B, y_B)$ accordingly - Figure 3.
The distance between k^{th} scatterer and the mobile is $l_{MS} = \| M - S_k \|$ and l_{MB} and l_{BS} can be calculated in a similar way.
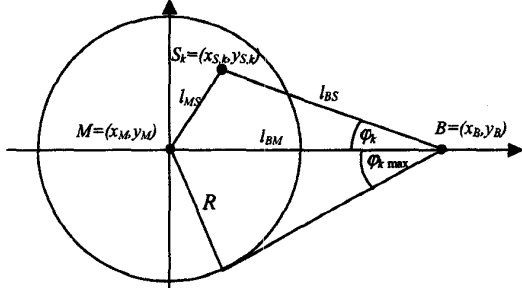

Figure 3: The geometry of the model.

The angle of arrival of the kth multipath component is:

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

The length and time of arrival of the multipath ray due to the kth scatterer are given by:

$$l_k = \| M - S_k \| + \| B - S_k \| = l_{MS,k} + l_{BS,k} \qquad (3)$$

The time of arrival – TOA is given by:

$$ToA_k = \frac{l_k}{c} \qquad (4)$$

Where c is the speed of light. The kth multipath due to the kth scatterer can be expressed as:

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

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:

$$f_{Dop,k} = \frac{-1}{\lambda} \frac{dl_k(t)}{dt} \qquad (6)$$

Based on (6), the discrete (if one harmonic is transmitted) Doppler spectrum centred at $f_c = 0$ Hz can be calculated as:

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

Where $\delta(.)$ is the Dirac function and Δd is the distance covered by the MS within 1 time step Δt with velocity V, $(\Delta d = \Delta t \ V)$.
The angular spread of the channel can be described by the probability density function (pdf) of the angle of arrival. The simplest formula for the pdf of AoA for such a model is due to [6]:

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

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 [6].

III. MULTIPATH COMPONENTS' LIFETIME

As the mobile travels, some scatterers move out of the chosen disc of scatterers while some 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 and then disappear ("multipath recombination"). Clearly, the duration t is a random variable described by some probability density function and it also depends upon the velocity V of the mobile and the scattering disc radius R. In the case of a uniform distribution of scatterers, 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 - Figure 4. The variable x has a uniform distribution since the marginal distribution across a line containing the diameter is uniform, hence:

$$f_x(x) = \frac{1}{2R} \quad ; -R \le x \le R \qquad (9)$$

The transformation between variables x and y is given by a simple relation: $y = g(x) = 2\sqrt{R^2 - x^2}$. Now it is possible to find the pdf $f_y(y)$ from (9) and the function $g(x)$:

$$f_y(y) = \sum_{i=1}^{m} f_x(w_i(y)) |J_i| \qquad (10)$$

Where: $J = \dfrac{dx}{dy} = w'(y)$ 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: $w_1(y) = \sqrt{R^2 - \left(\dfrac{y}{2}\right)^2} = -w_2(y)$. The Jacobians are:

$$\frac{dx_1}{dy} = -\frac{dx_2}{dy} = \frac{-y}{4\sqrt{R^2 - \left(\frac{y}{2}\right)^2}} \quad (11)$$

Hence the desired pdf is:

$$f_y(y) = \frac{y}{4\sqrt{R^2 - \left(\frac{y}{2}\right)^2}}[f_x(w_1(y)) + f_x(w_2(y))] \quad (12)$$

From (9) can be seen that $f_x(w_1(y)) = f_x(w_2(y)) = \frac{1}{2R}$, and also since $y = Vt$, then the probability density function of the time duration t for any given radius R and the mobile velocity V is given by:

$$f_t(t) = \begin{cases} \dfrac{tV}{4R\sqrt{R^2 - \left(\dfrac{tV}{2}\right)^2}} & 0 \le t \le 2\dfrac{R}{V} \\ 0 & otherwise \end{cases} \quad (13)$$
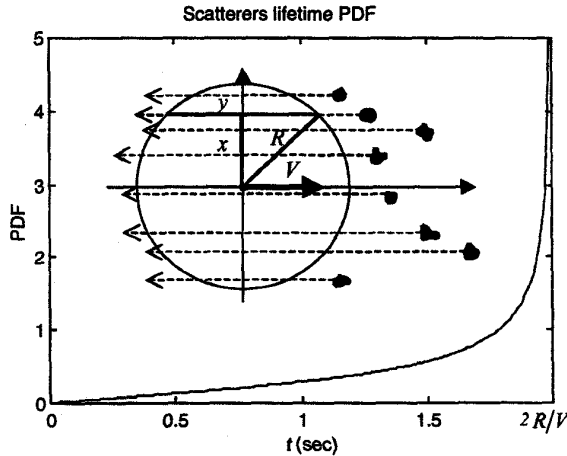

Figure 4: The probability density function of the multipath components' lifetime; inside – derivation scenario.

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

$$E[t] = \int_{-\infty}^{\infty} t f_t(t) dt = \frac{\pi R}{2V} \quad (14)$$

A plot of the probability density function of the scatterers' lifetime is depicted in Figure 4. It can be seen from Figure 4 and (13) that the pdf of the time duration approaches infinity for $t = 2R/V$, i.e. when the diameter of the scattering cluster aligns with a trace of a scatterer. Nevertheless, this is not a problem because since the pdf is continuous the probability of such an event happening is zero.

IV. DIFFERENT ENVIRONMENTS

Different propagation scenarios have different impact on the channel impulse response, and this must be taken into account if a realistic model is to be built. The mobile

radio propagation channels can be categorised based on the size of the cells and the height of the base station antennas into macro, micro and pico cells. The presented model is intended to simulate macro and micro cellular environments. Microcells have typical cell radii in the order of hundreds of meters, the base station antenna heights are less than the height of the surrounding rooftops, and they are employed in urban areas, especially in city centres, in order to solve capacity problems. Macrocells on the other hand can have radii in the order of several kilometres and the base station antennas are mounted above rooftops. Macrocells can be found in large variety of environments, and this allows for a further classification based on environmental characteristics, to urban, suburban and rural cells. A detailed description of different channel types can be found in [5].

Table 1 lists two basic input parameters from the model viewpoint. The values of both parameters (scattering cluster radius and scatterers area density) are based on results from extensive measurement campaigns reported in [5]. Although the area density of the scatterers is not explicitly stated in [5], it can be easily obtained from the information provided for the number of scatterers in a given disc. Clearly, it is also possible to incorporate the line-of sight component with predefined Rician K factor for chosen channel types. The complete description of all the input parameters is provided in [7].

Table 1 Parameters for different environments

Macrocell Urban	
Scatterers density area	$70 < \sigma < 600$ [scat/km^2]
Radius of the scat. cluster	100 m $\le$ R ≤ 300m
Macrocell Sub-urban	
Scatterers density area	$10 < \sigma < 35$ [scat/km^2]
Radius of the scat. cluster	300 m $\le$ R ≤ 500m
Macrocell Rural	
Scatterers density area	$3 < \sigma < 7$ [scat/km^2]
Radius of the scat. cluster	500 m $\le$ R ≤ 800m
Microcell Urban	
Scatterers density area	$7000 < \sigma < 60000$ [scat/km^2]
Radius of the scat. cluster	10 m $\le$ R ≤ 30m

V. SIMULATION RESULTS

A typical fading envelope as seen by one antenna element at the base station, is depicted in Figure 5. In general, the received signal is spread across full Doppler range $(-f_{Dopmax} < f < +f_{Dopmax})$ and it is independent of the scattering cluster size, hence the fading ratio is similar for all channel types. However, the fading ratio is not fixed within a simulation run due to non-stationary properties of the model resulting from $\dfrac{\partial^2 l_k(t)}{\partial t^2} \ne 0$ (as defined by (3)). It can be seen from the same figure that

the fading ratio of the modulus of the steering vectors is slower. This is due to the minor angle spread that the multipath components undergo in the sub-clusters. The fading ratio of the steering vectors depends upon the distance from the mobile station. The closer the sub-cluster is to the mobile, the higher the fading ratio of the steering vector. Since the presented model is driven by the GBSR assumptions, other characteristics like: time spread, angle spread, and correlation functions between antenna elements remain essentially the same as for the GBSR channel model.
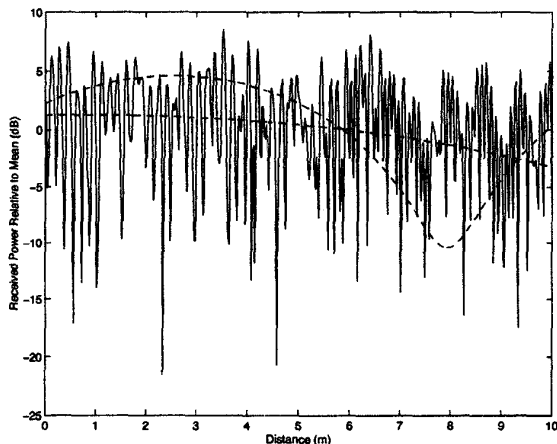

Figure 5: Typical fading from the superposition of all the multipaths: solid line; two typical fluctuations of the steering vectors' modulus: two dashed lines.

VI. CONCLUSIONS

The spatio-temporal propagation model proposed in this paper alleviates problems encountered in known statistical channel models. A hybrid approach which combines two classes of radio channel models, the GBSR and the GWSSUS, has been proposed in order to simultaneously exploit the advantages and minimise the disadvantages of both classes of models. An extension to the proposed hybrid model includes the generation of consecutive snapshots based on a moving scattering cluster. This extension introduces temporal characteristics to consecutive channel impulse responses and hence makes them correlated, which is more representative of reality. This allows also for direct calculation of the correlation functions, since complex envelopes are available. A further extension included in the proposed model is that the number of multipaths is no longer kept fixed as the mobile station moves but instead, it follows a random process with Poisson distributed values. Clearly, the fully time variant channel impulse response generated by the model presented here is beneficial for many applications and in particular for assessing tracking algorithms for adaptive antennas.

APPENDIX: PDF of the number of multipath components

Let the scattering cluster area be denoted by A and some larger area by Ω where $A \subset \Omega$ (Ω - might be the cell). If the scatterers 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:

$$\binom{n}{k} p^k (1-p)^{n-k} \cong \frac{1}{k!} N^k \left(1 - \frac{N}{n}\right)^{n-k} \qquad (15)$$

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

$$P(k) = \lim_{n \to \infty} \frac{1}{k!} N^k \left(1 - \frac{N}{n}\right)^{n-k} = \frac{N^k}{k!} e^{-N} = \frac{(A\sigma)^k}{k!} e^{-(A\sigma)} \qquad (16)$$

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

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