TWO-DIMENSIONAL EVOLUTIONAL SPECTRUM UNDER FADING CHANNEL

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Abstract: Broadband mobile communication systems experience fading over a wide frequency band. Most of the existing works on fading channel modelling assume wide-sense stationarity with respect to time and uncorrelated scattering w.r.t. delay. However, due to the time-varying movement of mobile terminals, fading is usually non-stationary w.r.t. time, i.e., the Doppler spectrum is non-stationary. To model non-stationary broadband mobile fading channels, in this project introduces a two-dimensional evolutionary spectrum (2D ES) approach, which is compatible with the power spectral density of a stationary process. Based on the 2D ES, an estimation method to estimate the 2D ES parameters from a trace of a fading process. In this project Nakagami-m fading channels are used which is non-stationary in both time and frequency domain. Developing SUI-3 2D ES based reference models further improves the non-stationary broadband channel modelling performance. This is a new research direction in the channel modelling.

Key words:-Two-dimensional evolutionary spectrum, non-stationary mobile fading channel, Nakagami-m fading, SUI channel model.

I. INTRODUCTION
To meet the demand of mobile users on high data rates, broadband communication is needed. A broadband channel poses significant challenges to the design of mobile communication systems due to time dispersion (delay spread) and frequency dispersion (frequency spread)[1]. An accurate and concise broadband channel model which characterizes both time and frequency dispersions is useful for channel simulation, performance evaluation and further design of broadband communication systems, especially for high speed vehicular transmissions. Usually, conventional broadband mobile fading channels have been characterized by wide-sense stationary (WSS) and uncorrelated scattering (US) fading channel models With WSS assumption, the Doppler effect caused by frequency dispersion can be described by the spectrum of channel gain process. To better characterize broadband mobile fading channels, it is of great importance to develop accurate and concise non-stationary channel models [2],[3].

In this paper, we extend the ES theory to 2D stochastic process, developing a 2D ES-based broadband channel modelling approach. Due to the fact that the auto correlation function of a 2D stochastic process is related to four variables at least, a 2D ES is not a simple product form or trivial linear combination of 1D ES. Based on 2D ES representation of the broadband fading channel, we discuss the 2D ES estimation and channel simulation in detail. The main contributions of this work can be summarized as follows.

- A complete 2D ES theory is established and used to simulate non-stationary broadband fading channels.
- Combining with filter model for stationary channel modelling, we present a broadband mobile fading channel simulator based on the 2D ES theory.
- We show that the 2D ES holds a strong compatibility in the sense that the 2D ES density of a WSSUS channel can be degraded as the scattering function of the channel.
- The proposed 2D ES theory is applied to analyze a class of Nakagami-m fading channels.
- Further, to improve the performance of channel model SUI channel is considered and the proposed 2D ES theory are applied to SUI channel model.

II. EVOLUTIONARY SPECTRUM FOR NON-STATIONARY BROADBAND FADING CHANNEL
First we introduce a 2D ES for non-stationary broadband mobile fading channels. Then we present how to estimate the 2D ES and evaluate the estimation error in detail.

A) The 2D ES representation of broadband mobile fading channels
Let us denote the complex channel gain of a broadband mobile fading channel by $h(t, \tau)$ where $t$ and $\tau$ represent the time and the delay, respectively. Usually, $h(t,\tau)$ is
referred to as the time variant impulse response of the channel. Following standard Fourier transform of \( h(t,\tau) \) w.r.t. \( \tau \), one obtains the time variant transfer function of the channel, denoted by \( H(t,\nu) \) where \( \nu \) represents the angle frequency variable of the transfer function.

Consider the auto correlation function (ACF) of \( H(t,\nu) \), i.e.,

\[
\text{RHH}(t_1,t_2;\nu_1,\nu_2)=\mathbb{E}[H^*(t_1,t_2)H(v_1,\nu_2)].
\]

Let us denote the Doppler shift variable by \( \omega \). According to Parzen’s work, there exist a family \( \{\psi_{\omega}(\omega,\tau)\} \) indexed by tuple \( (t,\nu) \) and a measure \( \mu(\omega,\tau) \) such that for any \( (t_1,v_1) \in \mathbb{R}^2 \) and \( (t_2,v_2) \in \mathbb{R}^2 \),

\[
\text{RHH}(t_1,t_2;v_1,\nu_2) = \int \psi^*_{t_1,v_1}(\omega,\tau)\psi_{t_2,v_2}(\omega,\tau)d\mu(\omega,\tau)
\]

Accordingly, \( H(t,\nu) \) can be represented as

\[
H(t,\nu) = \int \psi_{t,v}(\omega,\tau)dZ(\omega,\tau)
\]  

(2)

Let us select functions \( \{\phi_{t,\nu}(\omega,\tau)\} \) for a non-stationary channel as

\[
\psi_{t,v}(\omega,\tau) = \phi_{t,v}(\omega,\tau)\delta\left(\theta - \delta(\omega)\right)
\]  

(3)

The function of \((t,\nu)\), \( \phi_{t,v}(\omega,\tau) \), will be said to be an oscillatory function if, for some \((\theta(\omega),\delta(\tau))\), where \( D_{t,v}(\omega,\tau) \) is of the form

\[
D_{t,v}(\omega,\tau) = \int e^{i(\theta(\omega)\tau + \delta(\tau)v)}d\omega
\]

(4)

By redefining \( D_{t,v}(\omega,\tau) \) and the measure \( \mu(\omega,\tau) \) suitably, and further assuming the measure \( \mu(\omega,\tau) \) is absolutely continuous w.r.t. Lebesgue measure, one can write

\[
\text{RHH}(t_1,t_2;v_1,\nu_2) = \int D_{t_1,v_1}(\omega,\tau)D_{t_2,v_2}(\omega,\tau)e^{i\theta(\nu_2-\nu_1)}d\mu(\omega,\tau)
\]

(5)

Where \( d\mu(\omega,\tau) = S(\omega,\tau)d\omega d\tau \). Accordingly, one has

\[
E[H(t,\nu)|2] = |D_{t,v}(\omega,\tau)|^2S(\omega,\tau)d\omega d\tau
\]

(7)

Figure 1: The ES-Based Non-Stationary fading channel model

B) Estimating 2D ES for non-stationary channels

The basic idea for estimating ES is passing the stochastic process to a filter with sharp impulse response. Providing that the ES is smooth compared with the “frequency” response of the filter, i.e., the “frequency” response of the filter operates in that case only locally on the stochastic process, then the variance of the received process is approximately a scaled version of the ES of the original process. In this manner, one may hope to construct a suitable filter structure to estimate the 2D ES exactly. We first give a framework on the ES estimating and then evaluate the error between the estimation and the exact value of the ES.

Let us denote \( g(u,\xi) \) as a 2-D filter. For a general process \( H(t,\nu) \) which has an expression in the form of,

\[
Y(t,\nu) = g\left[u,\xi\right]H(t-u,\nu-\xi)e^{-j\omega(t-u)+\tau(\nu-\xi)}]
\]

(8)

Where \( (\omega_0,\tau_0) \in \mathbb{R}^2 \) is an arbitrary shift of \((\omega,\tau)\). For any \( t,\nu,\lambda_1,\lambda_2,\theta,\ell \), let us define

\[
G_{t,\nu,\lambda_1,\lambda_2}(\theta,\ell) = \int g\left[u,\xi\right]e^{jD_{t-u,v}(\lambda_1,\lambda_2)}e^{-j(\theta u + \ell \tau)}d\xi
\]

\[
Y(t,\nu) = \int G_{t,\nu,\omega+\alpha(t-t_0)+\tau_0}(\omega,\tau)e^{j(\omega t + \nu \tau)}D_{t,v}(\omega,\tau+\tau_0)dZ(\omega,\tau + \tau_0)
\]

(9)

As \( \{Z(\omega,\tau)\} \) are orthogonal processes, one further has
\[
\mathbb{E}[|Y(t, \nu)|^2] = \int \int |G_{t, v, \omega + \omega_0, \tau + \tau_0}(\omega, \tau)|^2 S(\omega + \omega_0, \tau + \tau_0) d\omega d\tau
\]  
(10)

III. SIMULATING BROADBAND MOBILE FADING CHANNELS UNDER NAKAGAMI-M FADING

In this section, we first present how to simulate a general broadband fading channel according to its 2D ES. Then we simplify the channel simulator for some special channels by analyzing the 2D ES.

a) General broadband mobile fading channel simulator

To generate a stationary fading channel \( H_s(t, \nu) \) with power spectrum density \( S(\omega, \tau) \), one may pass a white Gaussian process through \( H_s(t, \nu) \) a filter whose frequency response is \( S(\omega, \tau) \). Based on the 2D ES, to generate a non-stationary fading channel, we need to find a stationary process \( H_s(t, \nu) \) as stimulus and pass it through a proper time-frequency varying filter as illustrated in Fig. 1. For a given ES density function \( S_{t, \nu}(\omega, \tau) = |D_{t, \nu}(\omega, \tau)|^2 S(\omega, \tau) \), let us take inverse Fourier transform of \( S_{t, \nu}(\omega, \tau) \) w.r.t \( \omega \) and \( \tau \), for fixed \( t \) and \( \nu \), i.e.,

\[
k_{t, \nu}(u, \xi) = \int \int S_{t, \nu}(\omega, \tau)e^{i(\omega u + \tau \xi)} d\omega d\tau
\]

Figure 2: The ES-based simulation diagram for general broadband mobile fading channel \( h(t, \tau) \). \( X(t) \) and \( Y(t) \) are the transmitted and received signals of the communication system.

b) Two-Dimensional ES for Non-WSS but US Fading Channels

Recall that for US channels, different resolved delay taps are independent of each other, which may help simplify the channel simulator. From the independence, one has

\[
R_{hh}(t_1, t_2; \tau_1, \tau_2) = E[h^*(t_1, \tau_1)h(t_2, \tau_2)]
\]

(11)

Where \( S_{hh}(t_1, t_2; \tau) \) is the ACF of \( h(t, \tau) \) with the same tap index \( \tau \) [4]. Instead of decomposing \( R_{hh}(t_1, t_2; \tau) \), we can express \( S_{hh}(t_1, t_2; \tau) \) as

\[
S_{hh}(t_1, t_2; \tau) = p(\tau) \int A_{t1_s}(\omega)A_{t2_s}(\omega)e^{j\omega(t_2 - t_1)} q(\omega) d\omega
\]

(12)

Where \( p(\tau) \) is the delay PSD. This provides a 2D ES representation for time-variant impulse response. According to [19], one can use \( A_{t1_s}(\omega)q(\omega) \) and white Gaussian process to generate a non-WSS process for each tap. Concatenated with another gain \( \sqrt{p(\tau)} \), the generated process produces \( h(t, \tau) \), the tap gain of the broadband mobile fading channel corresponding to delay \( \tau \). In Fig. 3, we depict the simulation diagram of the non-WSS channels satisfying US assumption. More specifically, in Fig. 3, \( \{H^{(i)}_{t}(\nu)\}^{n} \) are \( n \) independent white Gaussian processes and \( k_{t, \nu}(u) \) is the impulse response of the time-varying filter corresponding to the \( i \)-th tap. Based on the 2D ES representation in Eq. (29), \( k_{t, \nu}(u) \) can be obtained by inverse Fourier Transform from \( A_{t_s}(\omega)q(\omega) \), that is,

\[
k_{t, \nu}(u) = \int A_{t_s}(\omega)q(\omega)e^{j\omega u} d\omega.
\]

(13)

Convoluted with \( k_{t, \nu}(u) \), each process is Doppler effect embedded. Finally, each process should be amplified with \( \sqrt{p(\tau)} \) to simulate the channel gain \( h(t, \tau_1) \). If the channel is WSS, then \( t \) can be removed from \( A_{t_s}(\omega) \). In this case, the product of \( p(\tau) \) and \( A_{t_s}(\omega)q(\omega) \) become the traditional scattering function of the WSS US channel, i.e.,

\[
S(\omega, \tau) = p(\tau)A_{t_s}(\omega)q(\omega).
\]

(14)
If $A_2(\omega)$ is not related to $\tau$, then $S(\omega, \tau)$ corresponds to the scattering function of the independent time-frequency dispersive channel.

It is noteworthy that $R_{HH}(t_1, t_2; v_1, v_2)$ can be obtained from $R_{hh}(t_1, t_2; t_1, t_2)$ via Fourier transform from the $\tau$-domain to $\vartheta$-domain. One can also algorithm 3.1 to simulate the non-WSS mobile fading channel satisfying the US assumption.

c) Two-Dimensional ES for Non-US but WSS Fading Channels

Another class of mobile fading channel is non-US but WSS channels. As the delay to the time domain is dual with the Doppler shift to the frequency domain, the WSS but non-US channel is dual with the non-WSS channel satisfying US assumption. Consider the Fourier transform of $H(t, v)$ w.r.t. $t$, $T(\omega, v)$. It is usually called as the of the channel. More specifically, according to [4], the received signal at frequency $\omega$, denoted by $Y(\omega)$ can be regarded as the sum of several Doppler shifted transmitted signals $X(\omega)$ amplified with corresponding Doppler variant transfer function $T(\omega, \omega - \theta)$, i.e.,

$$Y(\omega) = \int X(\omega - \theta)T(\omega, \omega - \theta) d\theta$$  (15)

Based on the wide sense stationary of $h(t, \tau)$, one has

$$R_{TT}(\omega_1, \omega_2; v_1, v_2) = E[T^*(\omega_1, v_1, \omega(v_2, v_2))] = \delta(\omega_1 - \omega_2)R_{TT}^*(\omega; v_1, v_2)$$

(16)

Where $R_{TT}^*(\omega; v_1, v_2)$ is the ACF of $T(\omega, v)$ with the same angle frequency $\omega$ [4]. Similarly, we can decompose $R_{TT}^*(\omega; v_1, v_2)$ as

$$R_{TT}^*(\omega; v_1, v_2) = q(\omega) \int B_{\omega, v_1}(\tau)e^{iH(v_1-v_2)p(\tau)d\tau}$$

(17)

Where $q(\omega)$ is the Doppler PSD. Based on the duality of WSS non-US channel and non-WSS US channel, one can use a simulation diagram similar to Fig. 3 to simulate the channel. Note that the transmitted and received signal should also be replaced with their frequency form which is not intuitive. Therefore, it may be better to adopt $R_{HH}(t_1, t_2; v_1, v_2)$ and Algorithm 3.1 to simulate this class of fading channel.

d) Non-stationary Nakagami-m broadband mobile fading channel simulator

We consider that the Nakagami-m fading channel is time-frequency independent dispersive. According to 2-D ES, $C_{HH}(t_1, t_2; v_1, v_2)$ can be represented by

$$C_{HH}(t_1, t_2; v_1, v_2) = \int A_{t_2}\, A_{t_1, v_1}(\omega)$$

Note that we use terms with wide tilde to distinguish the ES form of $C_{HH}(t_1, t_2; v_1, v_2)$ from that of $R_{HH}(t_1, t_2; v_1, v_2)$.

Algorithm 4.2 shows an ES-based channel simulator that generates a non-stationary Nakagami-m fading process, given user specified $c_{e, v}$ and $\rho(\tau, \omega)$. [4]

IV. PROPOSED METHOD

A) Stanford University Interim (SUI) channel

The general structure of SUI channel model is shown in Fig. 4. This structure is generally used for MIMO channels and this includes other configurations such as Single Input Single Output (SISO) and Single Input Multiple Output (SIMO) as subsets. The structure is the same for the primary and interfering signals in case of SUI channel. The basic components of the SUI channel models are

(A) Input Mixing Matrix,
(B) Tapped Delay Line, And
(C) Output Mixing Matrix.

Figure 3: Transmitter and receiver block diagram for SUI channel

The model parameters were selected based upon the statistical models. SUI channel models have 3 different types of terrain as shown in Table 1. Terrain C consisting of flat and light tree density so that the effects of the obstruction are low in this case. SUI-1 and SUI-2 are the channels taken into consideration to represent this type of terrain. The other two types of terrain models are B and A. The terrain B is characterized by flat/moderate tree density. SUI-3 and SUI-4 have been proposed for this type of terrain. The terrain A is characterized by a hilly area which contains moderate to heavy tree density.
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Table 1: Terrain of SUI model

<table>
<thead>
<tr>
<th>Terrain</th>
<th>Environmental Description</th>
<th>SUI Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Flat/Light Tree Density</td>
<td>SUI-1, SUI-2</td>
</tr>
<tr>
<td>B</td>
<td>Flat/Moderate Tree Density</td>
<td>SUI-3, SUI-4</td>
</tr>
<tr>
<td>A</td>
<td>Hilly/Moderate to Heavy Tree Density</td>
<td>SUI-5, SUI-6</td>
</tr>
</tbody>
</table>

4.2 The SUI-3 channel

In the paper, SUI-3 channel is used to improve the performance of channel model. The SUI-3 have been proposed under terrain B which is characterized by flat and moderate tree density.

Table 2: Characteristics of SUI-3 channel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tap1</th>
<th>Tap2</th>
<th>Tap3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay (μs)</td>
<td>0</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Power (Omni-directional Antenna) (dB)</td>
<td>0</td>
<td>-5</td>
<td>10</td>
</tr>
<tr>
<td>90% K-factor (Omni-directional)</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>75% K-factor (Omni-directional)</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Power (Omni-directional Antenna) (dB)</td>
<td>0</td>
<td>-1</td>
<td>-22</td>
</tr>
<tr>
<td>90% K-factor (Omni-directional)</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>75% K-factor (Omni-directional)</td>
<td>19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Doppler Shift (Hz)</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2 shows the characteristic of SUI-3 which has a terrain type B. The tap delay in this case is more than that of the earlier mentioned channel models. The system is considered again with an Omni-directional and a directional antenna which have a K-factor of 0.5 and 1.6 for Omni directional and 2.2 and 7 for directional for 90% and 75% respectively.

V. RESULTS

A) Nakagami-m Channel Results

We first examine the 2D ES at t = 500ms and ν = 7.5MHz for Nakagami-m fading with I = 0.5. The theoretical 2D ES and the estimated 2D ES are illustrated in Fig.4. The estimated 2D ES corresponds to non-stationary channel. Each point on the estimated 2D ES is the average of 50 times estimations. As illustrated in Fig. 4, due to the randomness of the simulation, the estimated 2D ES fluctuate slightly around the theoretical 2D ES. To quantify the gap between the two curved surfaces, we calculate the mean square error (MSE) between the theoretical result and the estimation value in Fig. 4. The MSE is equal to 0.0204. By regarding the 2D ES as a power distribution over delay and Doppler frequency (analogy of PSD of a stationary process), we find that the power of the estimated points which have estimation error less than the square root of the MSE account for 84.68% of the total power of the 2D ES.

Figure 4: Theoretical and Estimated 2-D ES at time and frequency tuple (t, ν) = (500ms, 7.5MHz)

To check whether the proposed estimation method can well track the time and frequency varying 2D ES, we also depict the theoretical 2D ES and its estimation at different tuples (t, ν) = (700ms, 10MHz) and (t, ν) = (900ms, 12.5MHz) in Fig. 5 and Fig. 6, respectively. In Fig. 5, there is also a gap between the estimated 2D ES and the theoretical one. The MSE of this case is 0.0209. Accordingly, the
estimated 2D ES points having an error less than the square root of MSE possess 78.6% of the total power. Similarly, in Fig. 6, the MSE between the theoretical 2D ES and estimated 2D ES is calculated as 0.0246. After identifying the points having an error less than the square root of MSE, we find that these points occupy 81.6% of the power of 2D ES.

The result obtained at various stage of extension method is shown below

B) SUI Channel Results

Figure 5: Theoretical and Estimated 2-D ES at time and frequency tuple (t,v)=(700ms,10MHZ)

Figure 6: Theoretical and Estimated 2-D ES at time and frequency tuple (t,v)=(900ms,12.5MHZ)

Figure 7: SUI-channel output of tuple (t,v)=(500ms,7.5MHZ)

Figure 8: SUI channel output of tuple (t,v)=(700ms,10MHZ)

Figure 9: SUI channel output of tuple (t,v)=(900ms,12.5MHZ)
Initially 2D ES approached under Nakagami-m Fading channel considering different tuples of (t,v). The accuracy is also shown by trace drivers. Later, 2D-ES is approached under SUI-3 channel which has a flat and moderate terrain for improving the performance. The output of SUI-3 is also shown at different tuples.

VI. CONCLUSION

A 2D ES theory was developed in this paper to model broadband mobile fading channels, especially for those channels dissatisfy WSS and US assumptions. In addition, we also presented a method for estimating the 2D ES of the broadband fading channel and evaluate the estimation error with terms related to the stationarity of the channel. Based on 2D ES, we established a corresponding broadband channel simulator. Simulation results indicated that the estimation of the 2D ES is quite good. It also indicated that the 2D ES-based Nakagami-m fading models is not enough to completely characterize all the non-stationary fading channels. Developing more 2D ES based reference models is promising to improve the non-stationary broadband channel modelling performance. This is a new research direction in the channel modelling.

So, SUI-3 channel is considered whose terrain is flat and moderate tree density and having low delay spread. Compared to the Nakagami-m fading channel SUI-3 channel shows better results in the simulation. It has more accuracy hence; it is a good channel modelling for mobile communication. The accuracy can also be improved further by considering better channel model than SUI-3.

REFERENCES