시공간 상관특성을 갖는 스마트 안테나용 결정적 레일레이 페이딩 모델

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Spatiotemporally Correlated Deterministic Rayleigh Fading Model for Smart Antenna Systems

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요 약

본 논문에서는 시공간 상관특성을 갖는 결정적 레일레이 페이딩 모델을 제안한다. 이 모델은 이동체 주위의 산란체에서 발생하는 신호들을 각 산란체들이 겪는 도플러 주파수들을 발진주파수로 하는 복소 발진기들로 모델링하고, 기지국 배열안테나에 대한 각 산란체들의 방향에 따른 방향 벡터들을 각각 곱하여 이들 더함으로써 시공간 상관특성을 갖는 페이딩 프로세스를 발생시킨다. 또한, 코드열간 교차 상관도가 낮은 Walsh-Hadamard 코드열들을 이용하여 서로 다른 다중 경로에 다른 Walsh-Hadamard 코드열들을 곱함으로서 다중 경로간 상관도가 낮은 다중 경로들을 발생시키는 광대역 다중 경로 페이딩 모델로 확장하였다.

ABSTRACT

This paper presents a spatiotemporally correlated Rayleigh fading model, which is based on the vector sum of scattered waves. Furthermore, employing Walsh-Hadamard codewords makes an extension to the wide-band multipath fading channel model in which uncorrelated multipaths with spatiotemporally correlated Rayleigh fading waveforms are generated.

Ⅰ. 서 론

Channel models including the spatial parameters have been proposed to design and evaluate the smart antenna systems [1]. Though a large number of channel models provide reliable models of AOA (angle of arrival), TOA (time of arrival), and delay spread [1], they have common lack of generating a group of spatiotemporally correlated M fading waveforms, which are associated with each antenna of an M-elements array. Recently, spatially and temporally correlated fading model, which implements temporally correlated fading process by means of Doppler filter and spatially correlated fading process by means of coloring matrix obtained from a desired spatial correlation matrix, is proposed in [2]. Though above model generates statistically rigorous fading waveforms in spatial and temporal domain, it needs a large number of Doppler filter tap coefficients to enhance the temporal correlation characteristics, which will significantly increase the operations [3].

This paper proposes a spatiotemporally correlat-

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ed deterministic Rayleigh fading model, which implements spatiotemporally correlated fading process by the vector sum of the complex sources with Doppler frequencies experienced by each scatterers. In addition, employing Walsh-Hadamard codewords makes an extension to the wide-band multipath fading model, which generates uncorrelated multipaths with spatiotemporally correlated Rayleigh fading waveforms. The model has advantages such as computing efficiency and applicability to the simulation of the smart antenna systems in the uplink and downlink by introducing the spatial coordinates of the mobile and the base station (BS).

Ⅱ. Spatiotemporally correlated deterministic Rayleigh fading model

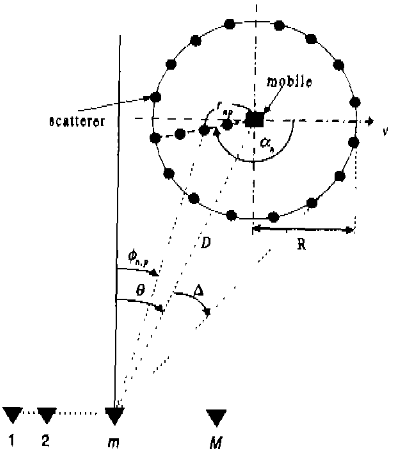


Fig. 1 Uniformly distributed disk of scatterer model

Consider a uniformly distributed disk of scatterer model in which the P scatterers are placed on each of N radial lines, and thus a total of $N \times P$ scatterers is placed uniformly on a disk about the mobile as shown in Fig.1. Assuming that $N \times P$ equal-strength rays arrive at the array antenna with AOA $\phi_{n,p}$, such that rays from P scatterers on the nth radial line experience a Doppler shift $f_n = f_d \cos(\alpha_n)$, where f_d is maximum Doppler frequency and $\alpha_n = 2\pi(n-0.5)/N$, spatiotemporally correlated M fading waveforms for M-elements array with antenna spacing d are given as follows

$$r(t) = \frac{1}{\sqrt{N}} \frac{1}{P} \sum_{n=1}^{N} \sum_{p=1}^{P} \exp[-j2\pi((f_c + f_n)\tau_{n,p} - f_n t)] \cdot v(\phi_{n,p}) \tag{1}$$

where f_c is carrier frequency and $\tau_{n,p}$ is time delay dependent on the distance between BS and the pth scatterer on the nth radial line. A $M \times 1$ steering vector $v(\phi)$ with AOA ϕ is defined as $[1\ \exp(j2\pi d \sin(\phi)/\lambda)\ \cdots\ \exp(j2(M-1)\pi d \sin(\pi)/\lambda)]^T$ where λ is the wavelength of the carrier and the superscript denotes the transpose.

It is desirable that the phase of each row of $r(t)$ be uniformly distributed. This can be accomplished by two conditions such as zero correlation between real and imaginary part of each row of $r(t)$ and equal variance of real and imaginary parts of each row of $r(t)$. Thus, $r(t)$ can be refined as

$$r(t) = \frac{1}{\sqrt{N}} \frac{1}{P} \sum_{n=1}^{N} \sum_{p=1}^{P} (\cos(\beta_n) + j\sin(\beta_n)) \cdot \exp(j(2\pi f_n t + \eta_{n,p})) \cdot v(\phi_{n,p}) \tag{2}$$

where initial phases $\eta_{n,p} = -2\pi(f_c + f_n) \cdot \tau_{n,p}$ are uniformly distributed in $[-\pi, \pi]$, because a small path delay $\tau_{n,p}$ cause a large change in the phase $\eta_{n,p}$. By choosing $\beta_n = 4\pi n/N$, the above two conditions for the uniformly distributed phases are satisfied. AOA of each scatterer is given by

$$\phi_{n,p} = \theta + \frac{r_{n,p}}{D} \sin(\alpha_n) \tag{3}$$

where $r_{n,p} = R\sqrt{p/P}$ is determined by the spatial PDF of the scatterers.

The deterministic fading model has the inherent problem that it is difficult to generate uncorrelated multiple fading waveforms, because there is a significant crosscorrelation between the multiple fading waveforms generated by Jakes' method, which sets distinct initial phases to different fading waveforms [3]. One method, in which Walsh-Hadamard codewords weight the outputs of the oscillator before summing, has been proposed by Dent [4]. The oscillator corresponds to the sum of the four scatterers with the same Doppler frequency. In this paper, Walsh-Hadamard codewords are employed to weight the complex outputs of each scatterers. Thus, with N a power of two, the lth path with spatiotemporally correlated Rayleigh fading waveforms can be generated by

$$\begin{aligned} r(t)= & \frac{1}{\sqrt{N}}\frac{1}{P}\sum_{n=1}^{N}\sum_{p=1}^{P}H_l(n)(\cos(\beta_n)+j\sin(\beta_n))\cdot \\ & \exp(j(2\pi f_n t+\eta_{n,p}))\cdot v(\phi_{n,p}) \end{aligned} \tag{4}$$

where $H_l(n)$ is the lth Walsh-Hadamard code sequence in n (± 1 values). N sets of Walsh-Hadamard codewords make N orthogonal sets of initial phases $\eta_{n,p}$ of scatterers. This gives $N/2$ uncorrelated multipaths, because $N/2$ multipaths, in which symmetric scatterers along the axis of the moving direction of the mobile are multiplied by the opposite sign, are canceled out. For example, N=64 gives 32 uncorrelated multipaths with M spatiotemporally correlated Rayleigh fading waveforms.

Assuming distinct AOA of paths, the space-time correlation matrix between $r_l(t)$ and $r_l(t+\tau)$ is given by

$$\mathrm{E}[\,r_l(t)\,r_l^H] = \begin{cases} J_0(2\pi f_d\tau)\cdot R_s^l, & l=k \\ 0, & l\neq k \end{cases} \tag{5}$$

where $(\cdot)^H$ denotes Hermitian transpose and R_s^l is the spatial correlation matrix of the lth path defined as

$$R_s^l=\frac{1}{\Delta_l}\int_{\theta_l-\Delta_l}^{\theta_l+\Delta_l} v(\zeta)\,v^H(\zeta)p_l(\zeta)d\zeta \tag{6}$$

$J_0(2\pi f_d\tau)$ shows the time correlation as a function of $f_d\tau$. And R_s is a function of θ, Δ, antenna spacing d, and $p(\zeta)$, which is the APS (Azimuthal Power Spectrum). A simple uniform disk model is employed in this paper, but an extension is possible by adapting the positions of the scatterers according to the desired APS such as Gaussian or Laplacian distribution. The spatial correlation matrix R_s can be derived by analytical or numerical integration of (6), and it reveals spatial correlation characteristics. The theoretical envelope correlation for the uniform disk model is derived analytically in [5] as below

$$\begin{aligned} \rho_{env}(d)= & [J_0(2\pi d\Delta\cos(\theta))+J_2(2\pi d\Delta\cos(\theta))]\cdot \\ & \exp(-j2\pi d\sin(\theta)) \end{aligned} \tag{7}$$

Ⅲ. Implementation and Results

The expression (4) can be further simplified to

$$\begin{aligned} r(t)= & \frac{1}{\sqrt{N}}\frac{1}{P}\sum_{n=1}^{N}\sum_{p=1}^{P}H_l(n)(\cos(\beta_n)+j\sin(\beta_n))\cdot \\ & \exp(j(2\pi f_n t+\eta_n))\cdot v_p(\phi_n) \end{aligned} \tag{8}$$

where the sum of the steering vector of individual scatterer on the same radial line is expressed as a single aggregate steering vector. The aggregate steering vector for P scatterers on nth radial line is defined by

$$v_p(\phi_n)=\frac{1}{P}\sum_{p=1}^{P}\exp(j(\eta_{n,p}-\eta_n))\cdot v(\phi_{n,p}) \tag{9}$$

The structure of the simulator generating $N/2$ uncorrelated multipaths with M spatiotemporally correlated Rayleigh fading waveforms is shown in Fig.2. The complex sources with Doppler frequencies experienced by each scatterers are multiplied by their steering vectors depending on the direction of scatterers relative to antenna array, weighted by Walsh-Hadamard code sequences, and summed up.

For any given instant of time, the steering vector of the received signals arrive from different directions and their initial phases will be different, and so they will add up either constructively or destructively at each point across the array depending on the relative phase relationship. And for any antenna element, the Rayleigh distributed signal levels are varying with time. Fig.3a and Fig.3b show the fading envelopes when $\theta=0°$, R=50m and D=1000, 2000m. Comparison between

Fig.3a and Fig.3b shows that the signal level across the array will change more rapidly as D decreases.

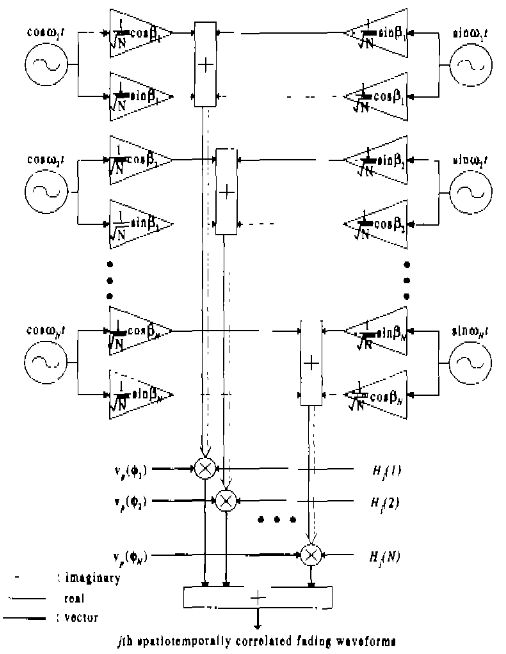
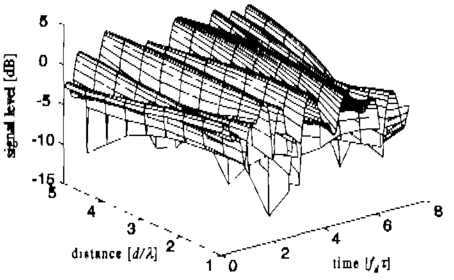
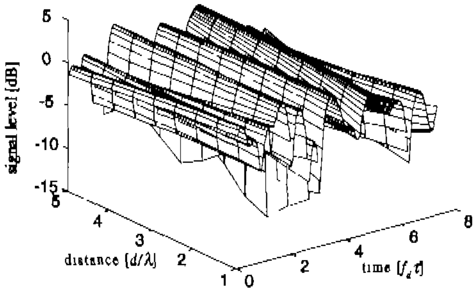


Fig. 2 Simulator generating uncorrelated multipaths with M spatiotemporally correlated Rayleigh fading



(a) D=1000m



(b) D=2000m

Fig. 3 Fading envelopes when $\theta = 0°$, R=50m

In the spatiotemporally correlated deterministic Rayleigh fading model, level crossing rate (LCR), temporal autocorrelation, spatial correlation, and crosscorrelation characteristics between paths are of great importance. Fig.4 shows that LCR agrees well with theory [3] when $N=64$.

Fig.5 shows the temporal autocorrelation when $N=64$, 128. Observe that the autocorrelation tends to deviate from the desired values at large lags, but improves as the number of scatterer increases. In Fig.6, the spatial correlation of the simulated cases of $D=500$m, 1000m, and 2000m are compared with the analytic results given in (7) where close agreement with theory is observed.

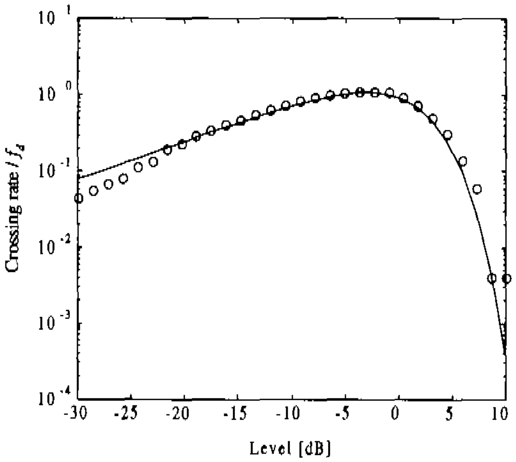


Fig. 4 Level crossing rate when $N=64$
(——— : theory, ○○○○ : simulation)

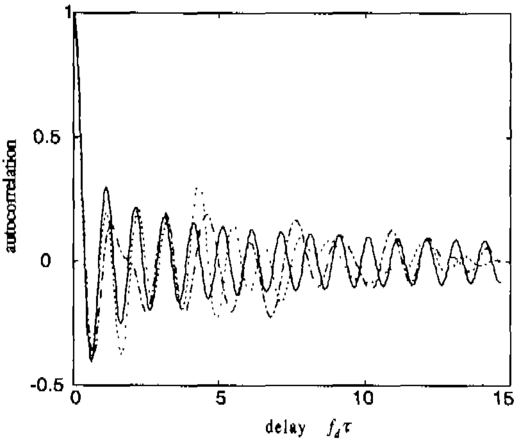


Fig. 5 Temporal autocorrelation when $N=64$,128
(———: theory, ········: $N=64$, -·-·-·-: $N=128$)

In Fig.7, the crosscorrelation between 1*st* and 2*nd* paths among multipaths generated by N=64 and 128 Walsh-Hadamard codewords are shown. Note that $N\geq 64$ give a tolerable crosscorrelation between paths and the crosscorrelation can be reduced by the longer Walsh-Hadamard codeword.

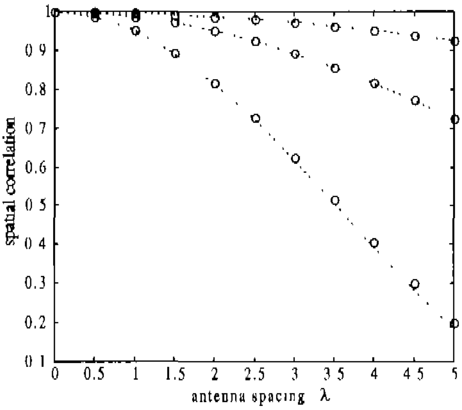


Fig. 6 Spatial correlation when D=500m, 1000m, and 2000m (N=128, P=20, R=50m)
(——— : theory, ○○○○ : simulation)

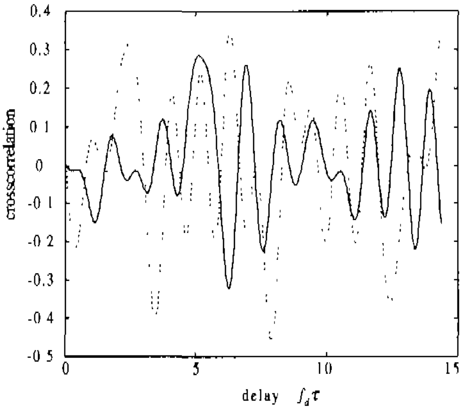


Fig. 7 Crosscorrelations between 1st and 2nd path when N=64 and 128
(——— : N=64, ……… : N=128)

Ⅳ. Conclusion

This paper presents a spatiotemporally correlated wide-band multipath Rayleigh fading model based on the vector sum of scattered waves. It can be seen that the statistical properties in time and space domain of the model are in good agreement with theory and the crosscorrelation between paths are reduced to a tolerable level. The model can be applied to evaluate the smart antenna systems and beamforming algorithms in the uplink and downlink by generating uncorrelated multipaths with spatiotemporally correlated Rayleigh fading waveforms from the mobile and inteferers with spatial coordinates relative to BS.

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