An Improved Deterministic SoS Channel Simulator for Multiple Uncorrelated Rayleigh Fading Channels

Cheng-Xiang Wang, *Member, IEEE,* Dongfeng Yuan, *Senior Member, IEEE,* Hsiao-Hwa Chen, *Senior Member, IEEE,* and Wen Xu, *Senior Member, IEEE*

***Abstract*—The generation of multiple uncorrelated Rayleigh fading waveforms is often demanded for simulating wideband fading channels, multiple-input multiple-output (MIMO) channels, and diversity-combined fading channels. In this letter, an improved deterministic sum-of-sinusoids (SoS) channel simulator with a new parameter computation method is proposed to simulate a large number of uncorrelated Rayleigh fading processes. Compared with the existing SoS channel simulators, the proposed deterministic SoS model yields a much better simulation efficiency while still preserving satisfactory approximations to the desired statistical properties of the reference model.**

***Index Terms*—Uncorrelated Rayleigh fading processes, sum-of-sinusoids channel simulator, parameter computation method, correlation properties.**

I. Introduction

THE sum-of-sinusoids (SoS) channel modeling approach has been extensively applied to the simulation of Rayleigh fading channels [1]–[15]. An SoS channel simulator can be either ergodic stochastic (deterministic) [2]–[6], [10]–[15] or non-ergodic stochastic [6]–[9] depending on the underlying parameters (gains, frequencies, and phases). For an ergodic stochastic SoS channel simulator, gains and frequencies are kept constant during simulation, while only phases are random variables [6], [14]. Due to the ergodicity, such a channel simulator needs only one simulation trial to represent its statistical properties. Its degenerated form or a single simulation trial results in a deterministic channel simulator, where all the parameters (gains, frequencies, and phases) are constants during simulation. A non-ergodic stochastic SoS channel simulator has at least one parameter (frequencies and/or gains) as random variables, the values of which vary for different simulation trials [6]. The relevant statistical properties of a non-ergodic stochastic SoS channel model also vary for each simulation trial and have to be calculated by averaging over a large number of simulation runs. In general, a deterministic SoS channel simulator has a better simulation efficiency than a non-ergodic stochastic SoS channel model.

A channel simulator capable of generating multiple uncorrelated Rayleigh fading waveforms is often required for simulating multiple-input multiple-output (MIMO) channels [16], wideband fading channels [7], and diversity-combined fading channels [15]. In order to generate multiple uncorrelated Rayleigh fading waveforms by using SoS channel simulators, different parameter computation methods [2]–[11] have been investigated. Jakes' method [2] and its derivatives [3]–[6] were designed for deterministic SoS channel simulators, which retain some undesirable statistical properties. The cross-correlation function (CCF) of any pair of underlying complex processes is generally not zero for the deterministic SoS models as given in [2]–[4]. For the models suggested in [5], [6], the autocorrelation functions (ACFs) of the inphase and quadrature components of each underlying complex process do not match closely to the desired ones. To remedy the drawbacks of the deterministic SoS channel simulators given in [2]–[6], non-ergodic stochastic SoS channel simulators were proposed in [6]–[9] with random parameters in the employed sinusoids. By averaging over a large number of simulation trials, the developed channel simulators in [6]–[9] can approximate closely the desired statistical properties but have a low simulation efficiency.

The method of exact Doppler spread (MEDS) [10] was revisited in [11] by investigating additional boundary conditions in order to produce multiple uncorrelated Rayleigh fading waveforms with a deterministic SoS channel simulator. A disadvantage with the MEDS is that large numbers of sinusoids have to be deployed when more than four uncorrelated Rayleigh processes are produced [11]. This will greatly increase the model complexity and therefore restrict the use of the underlying SoS channel simulator. In this letter, a new parameter computation method originating from the MEDS is proposed for deterministic SoS channel simulators capable of producing multiple uncorrelated Rayleigh fading waveforms without using large numbers of sinusoids. Compared to the existing SoS channel simulators shown in [2]–[11], the improved deterministic SoS channel simulator has superior simulation efficiency, while it can still achieve similar good or even better approximations to the desired statistical properties of the reference model.

The remaining of this paper is outlined as follows. Section II describes the reference model with its desired statistical properties. In this section, we also present the deterministic SoS simulation model and the conditions that must be fulfilled in order to generate multiple uncorrelated fading waveforms. In

Manuscript received March 30, 2007; revised August 16, 2007 and November 19, 2007; accepted November 19, 2007. The associate editor coordinating the review of this paper and approving it for publication was M. Win. The work presented in this paper was supported partly by the research grant from National Science Council of Taiwan, NSC 97-2219-E-006-004.

C.-X. Wang is with the Joint Research Institute for Signal and Image Processing, School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh, UK (e-mail: cheng-xiang.wang@hw.ac.uk).

D. Yuan is with the School of Information Science and Engineering, Shandong University, Jinan, China (e-mail: dfyuan@sdu.edu.cn).

H.-H. Chen is with the Department of Engineering Science, National Cheng Kung University, Taiwan (e-mail: hshwchen@ieee.org).

W. Xu is with Infineon Technologies AG, Neubiberg, Germany (e-mail: wen.xu@ieee.org).

Digital Object Identifier 10.1109/TWC.2008.070339.

Section III, a new parameter computation method is proposed and performance of the resulting deterministic SoS channel simulator is investigated. Finally, conclusions are drawn in Section IV.

II. Reference Model and Deterministic SoS Simulation Model

Our aim is to produce $\mathcal{L}$ uncorrelated Rayleigh fading processes

$$\zeta_\ell(t) = \Big|\mu_\ell(t)\Big| = \Big|\mu_{1,\ell}(t) + j\mu_{2,\ell}(t)\Big|, \quad \ell = 1,2,\ldots,\mathcal{L} \tag{1}$$

where $j = \sqrt{-1}$ and $\mu_\ell(t)$ is a complex Gaussian random process with zero-mean. The inphase component $\mu_{1,\ell}(t)$ and quadrature component $\mu_{2,\ell}(t)$ are uncorrelated real Gaussian random processes, i.e., $r_{\mu_{1,\ell}\mu_{2,\ell}}(\tau) = r_{\mu_{2,\ell}\mu_{1,\ell}}(\tau) = 0$, with common variance σ_0^2 and identical ACFs. The CCF of any pair of complex Gaussian random processes must be zero, i.e., $r_{\mu_\ell\mu_\lambda}(\tau) = 0$ for $\ell, \lambda = 1,2,\ldots,\mathcal{L}$ with $\ell \neq \lambda$. Assuming a two-dimensional isotropic scattering environment [1], the ACF $r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ of $\mu_{i,\ell}(t)$ (i=1, 2) for the reference model is [2]

$$r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau) \quad = \quad \sigma_0^2 J_0(2\pi f_{\max}\tau) \tag{2}$$

where $J_0(\cdot)$ denotes the zeroth-order Bessel function of the first kind and $f_{\max} = v f_c/c$ is the maximum Doppler frequency. Here, v represents the mobile speed, c is the speed of light in free space, and f_c is the carrier frequency. Since $r_{\mu_{1,\ell}\mu_{2,\ell}}(\tau) = r_{\mu_{2,\ell}\mu_{1,\ell}}(\tau) = 0$, the ACF of the complex Gaussian random process $\mu_\ell(t)$ is $r_{\mu_\ell\mu_\ell}(\tau) = 2r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau) = 2\sigma_0^2 J_0(2\pi f_{\max}\tau)$ [2], [11]. The objective of the proposed SoS channel simulator is then to reproduce accurately and efficiently the above desired statistical properties.

By invoking the central limit theorem, a Gaussian random process can be approximated by the superposition of a large number of properly selected sinusoids. Based on this principle of the SoS channel simulators, the ℓth ($\ell = 1,2,\ldots,\mathcal{L}$) Rayleigh fading process is modeled as

$$\tilde{\zeta}_\ell(t) = \Big|\tilde{\mu}_\ell(t)\Big| = \Big|\tilde{\mu}_{1,\ell}(t) + j\tilde{\mu}_{2,\ell}(t)\Big| \tag{3}$$

where

$$\tilde{\mu}_{i,\ell}(t) = \sum_{n=1}^{N_{i,\ell}} c_{i,n,\ell}\cos\Big(2\pi f_{i,n,\ell}t + \theta_{i,n,\ell}\Big)\ , \quad i = 1,2\ . \tag{4}$$

Here, $N_{i,\ell}$ denotes the number of sinusoids, $c_{i,n,\ell}$, $f_{i,n,\ell}$, and $\theta_{i,n,\ell}$ are the gains, discrete frequencies, and phases, respectively. Note that all the above simulation model parameters will be kept constant during simulation. This indicates that $\tilde{\mu}_{i,\ell}(t)$ is a deterministic function and the statistical properties of the resulting deterministic SoS channel simulator must be calculated by using time averages instead of statistical averages.

The time-averaged ACF $\tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ of $\tilde{\mu}_{i,\ell}(t)$ can be expressed as

$$\tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau) \quad = \quad \sum_{n=1}^{N_{i,\ell}} \frac{c_{i,n,\ell}^2}{2}\cos\Big(2\pi f_{i,n,\ell}\,\tau\Big) \tag{5}$$

It has been shown in [10], [11] that the different processes $\tilde{\mu}_{i,\ell}(t)$ and $\tilde{\mu}_{k,\lambda}(t)$ ($i,k = 1,2$ and $\ell,\lambda = 1,2,\ldots,\mathcal{L}$, where $i = k$ and $\ell = \lambda$ do not hold at the same time) are uncorrelated, i.e., $\tilde{r}_{\mu_{i,\ell}\mu_{k,\lambda}}(\tau) = 0$, if and only if

$$f_{i,n,\ell} \neq \pm f_{k,m,\lambda} \tag{6}$$

holds for all $n = 1,2,\ldots,N_{i,\ell}$ and $m = 1,2,\ldots,N_{k,\lambda}$. In other words, the discrete frequencies for different uncorrelated processes must be orthogonal. The fulfillment of the inequality (6) will also result in $\tilde{r}_{\mu_{1,\ell}\mu_{2,\ell}}(\tau) = r_{\mu_{1,\ell}\mu_{2,\ell}}(\tau) = 0$, $\tilde{r}_{\mu_{2,\ell}\mu_{1,\ell}}(\tau) = r_{\mu_{2,\ell}\mu_{1,\ell}}(\tau) = 0$, and $\tilde{r}_{\mu_\ell\mu_\lambda}(\tau) = r_{\mu_\ell\mu_\lambda}(\tau) = 0$. Consequently, the ACF $\tilde{r}_{\mu_\ell\mu_\ell}(\tau)$ of the ℓth complex waveform $\tilde{\mu}_\ell(t)$ can be written as $\tilde{r}_{\mu_\ell\mu_\ell}(\tau) = \tilde{r}_{\mu_{1,\ell}\mu_{1,\ell}}(\tau) + \tilde{r}_{\mu_{2,\ell}\mu_{2,\ell}}(\tau)$. In what follows, a new parameter computation method will be introduced to address the issues on how to properly design $f_{i,n,\ell}$ under the constraint (6).

III. A New Parameter Computation Method

The proposed method originates from the MEDS [11], where the discrete frequencies are given by

$$f_{i,n,\ell} \quad = \quad f_{\max}\sin\Big[\frac{(2n-1)\pi}{4N_{i,\ell}}\Big]. \tag{7}$$

The only way to fulfill (6) with the MEDS in (7) is to guarantee that $N_{i,\ell}/N_{k,\lambda} \neq (2n-1)/(2m-1)$ for all $n = 1,2,\ldots,N_{i,\ell}$ and $m = 1,2,\ldots,N_{k,\lambda}$ [11]. With the increase of the required number of simulated uncorrelated fading processes, the numbers of sinusoids of the deterministic SoS channel simulator with the MEDS will increase almost exponentially. This obvious drawback prevents the applications of the MEDS to the simulation of a large number of uncorrelated processes.

To overcome the disadvantage of the MEDS, we propose to define the discrete frequencies as

$$f_{i,n,\ell} \quad = \quad f_{\max}\sin\Big[\frac{(2n-1)\pi}{4N_{i,\ell}}\Big] + S_{i,\ell} \tag{8}$$

where $S_{i,\ell}$ should be chosen as an infinitesimal real value, and its reason will become clear subsequently. The gains are given by $c_{i,n,\ell} = \sigma_0\sqrt{2/N_i}$ and the phases $\theta_{i,n,\ell}$ in (4) are simply considered as the outcomes of a random number generator uniformly distributed over $(0, 2\pi]$ [10], [11]. It can be observed from (8) that the proposed method will be reduced to the original MEDS in (7) if $S_{i,\ell} = 0$. This encourages us to name the proposed method as the modified MEDS (MMEDS), which includes the original MEDS as a special case.

In contrast to the MEDS, the introduction of the new quantity $S_{i,\ell}$ into the MMEDS relaxes the constraint of $N_{i,\ell}$ in order to fulfill (6). For simplicity, in this letter we choose $N_{i,\ell} = N_i = N$ ($i = 1,2$ and $\ell = 1,2,\ldots,\mathcal{L}$). Then, (8) can be rewritten as

$$f_{i,n,\ell} \quad = \quad f_{\max}\sin\Big[\frac{(2n-1)\pi}{4N}\Big] + S_{i,\ell}. \tag{9}$$

Since $1 \leq n \leq N$, we can conclude that $\pi/(4N) \leq (2n-1)\pi/(4N) \leq \pi/2 - \pi/(4N)$ holds. It follows from (9) that $f_{\max}\sin[\pi/(4N)] + S_{i,\ell} \leq f_{i,n,\ell} \leq f_{\max}\cos[\pi/(4N)] + S_{i,\ell}$ holds. Let us limit the values of $f_{i,n,\ell}$ in (9) to the interval $[0, f_{\max}]$. Thus, the following inequality

$$-f_{\max}\sin\Big(\frac{\pi}{4N}\Big) \leq S_{i,\ell} \leq f_{\max} - f_{\max}\cos\Big(\frac{\pi}{4N}\Big) \tag{10}$$

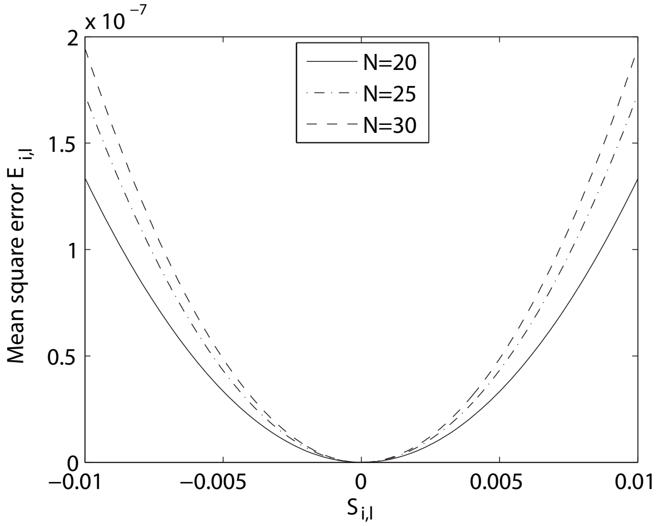

Fig. 1. The MSE $E_{i,\ell}$ of the ACF by using the MMEDS ($\sigma_0^2 = 1$, $f_{\max} =$ 91 Hz).

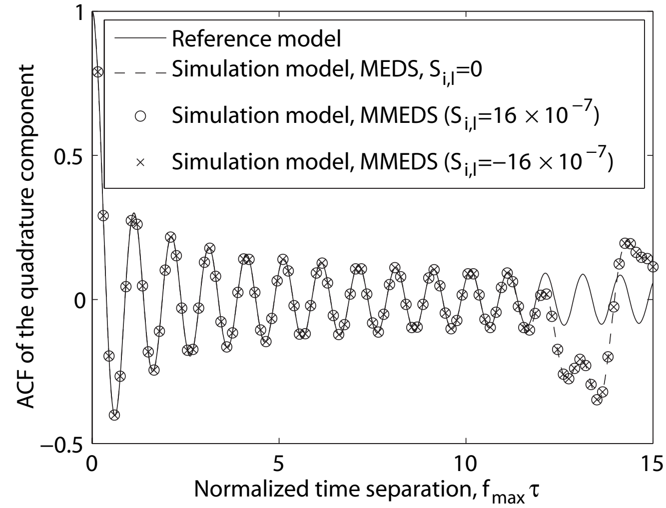

Fig. 2. The ACFs of the quadrature component for the reference model and the simulation model by using the MEDS and the MMEDS ($\sigma_0^2 = 1$, $N = 20$).

holds. By keeping (10) in mind, the substitution of (9) into (6) tells us that the following condition must be fulfilled

$$S_{i,\ell} - S_{k,\lambda} \neq f_{\max} \sin\Big[\frac{(2m-1)\pi}{4N}\Big] - f_{\max} \sin\Big[\frac{(2n-1)\pi}{4N}\Big] \tag{11}$$

for all $n, m = 1, 2, \cdots, N$, where $i, k = 1, 2$ and $\ell, \lambda = 1, 2, \ldots, \mathcal{L}$. Note that $i = k$ and $\ell = \lambda$ do not hold at the same time. Given any $f_{\max}$ and N, the values of the right hand side of the above inequality can easily be calculated. The selection of $S_{i,\ell}$ must be under the constraints of both (10) and (11).

In the following text, we will investigate the impact of $S_{i,\ell}$ on the approximation quality of $\tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau) \approx r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$. A widely used measure of the error between the approximate ACF $\tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ in (5) and the exact ACF $r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ in (2) is the mean-square error (MSE) defined by

$$E_{i,\ell} = \frac{1}{\tau_{\max}} \int_0^{\tau_{\max}} \Big[r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau) - \tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)\Big]^2 d\tau \tag{12}$$

where $\tau_{\max}$ denotes an appropriate time interval $[0, \tau_{max}]$ over which the approximation of $r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ is of interest. According to [10], [11], the value $\tau_{\max} = N/(2f_{\max})$ has turned out to be suitable. Fig. 1 shows a representative example of the MSE $E_{i,\ell}$ as a function of $S_{i,\ell}$ with different values of N. Here, we used the normalized variance $\sigma_0^2 = 1$ and $f_{\max} = 91$ Hz, which corresponds to a mobile speed of v=109.2 km/h and a carrier frequency of f_c=900 MHz. It can be observed clearly that for any given value of N, the MSE increases with the increase of the absolute value of $S_{i,\ell}$. The minimum MSE is obtained when $S_{i,\ell} = 0$. which indicates that the original MEDS provides the best fitting to the desired ACF $r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$. Fig. 1 actually suggests us that an infinitesimal value should be chosen for $S_{i,\ell}$ as long as (10) and (11) are satisfied. In this letter, we propose to define

$$S_{i,\ell} = (-1)^{i-1}\ell\varepsilon \tag{13}$$

where ε is an infinitesimal positive value, e.g., $\varepsilon = 10^{-7}$.

Using $f_{\max} = 91$ Hz and $N = 20$ as an example, we calculate the constraints of $S_{i,\ell}$ in (10) and (11). Let us assume $\mathcal{L} = 16$, which corresponds to, e.g., a 4×4 MIMO channel. It turns out to be that $\varepsilon = 10^{-7}$ in (13) can be taken so that for any given $\ell, \lambda = 1, 2, \ldots, \mathcal{L}$, the conditions (10) and (11) can be fulfilled. In Fig. 2 we compare the ACFs of the quadrature component for the reference model, the simulation model by using the MEDS ($\varepsilon = 0$) and the MMEDS with $\varepsilon = 10^{-7}$ and $\ell = \mathcal{L} = 16$. Here, $\sigma_0^2 = 1$ was used. It is noted that Fig. 2 presents the worst approximation results of the ACF $\tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ for the MMEDS with $S_{i,\ell} = \pm 16 \times 10^{-7}$, which are obtained when $\ell = \mathcal{L}$ in (13). For $\ell < \mathcal{L}$, the approximation results are better, which is also obvious from Fig. 1. On the other hand, even with the worst case, the resulting ACF for the MMEDS is nearly indistinguishable from that obtained by using the MEDS ($\varepsilon = 0$). For both the MEDS and MMEDS with the given parameters ε and ℓ, the approximation $\tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau) \approx r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ is excellent when $\tau \in [0, N/(2f_{\max})]$, i.e., $f_{\max}\tau \in [0, 10]$. Note that this conclusion holds for arbitrary values of $f_{\max}$, σ_0^2, and N. In case of $f_{\max}\tau > N/2$, the ACFs of the simulation model and reference model will diverge gradually and never converge again [11]. A better approximation over larger time delays can only be achieved with the increase of N. Due to the fact that short time delays, e.g., $f_{\max}\tau \leq 0.3$ [13], are of more interest for most communication systems, the MMEDS with small numbers of sinusoids N is actually an excellent method in terms of the above interested correlation properties.

By analogy with (12), we measure the quality of the approximation $\tilde{r}_{\mu_\ell\mu_\ell}(\tau) \approx r_{\mu_\ell\mu_\ell}(\tau)$ over the interval $[0, \tau_{\max}]$ with the following MSE

$$E_\ell = \frac{1}{\tau_{\max}} \int_0^{\tau_{\max}} \Big[r_{\mu_\ell\mu_\ell}(\tau) - \tilde{r}_{\mu_\ell\mu_\ell}(\tau)\Big]^2 d\tau \tag{14}$$

The behavior of E_ℓ is illustrated in Fig. 3 as a function of $S_{i,\ell}$ with various values of N. The comparison of Figs. 1 and 3 clearly demonstrates that E_ℓ is overall much smaller than

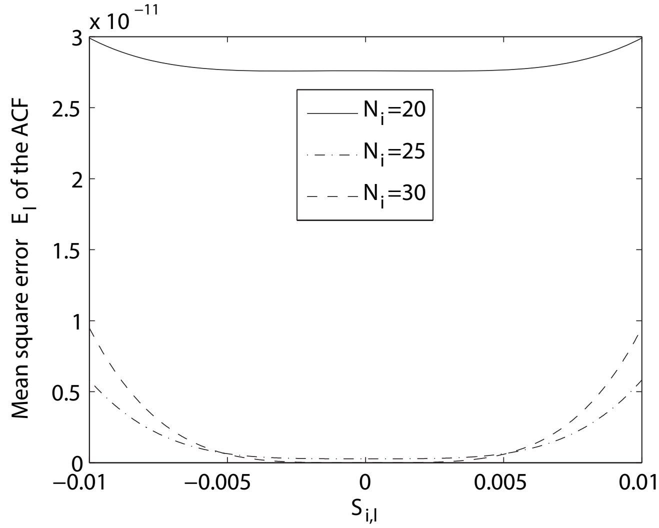

Fig. 3. The MSE E_ℓ of the ACF by using the MMEDS ($\sigma_0^2 = 1$, $f_{\max} = 91$ Hz).

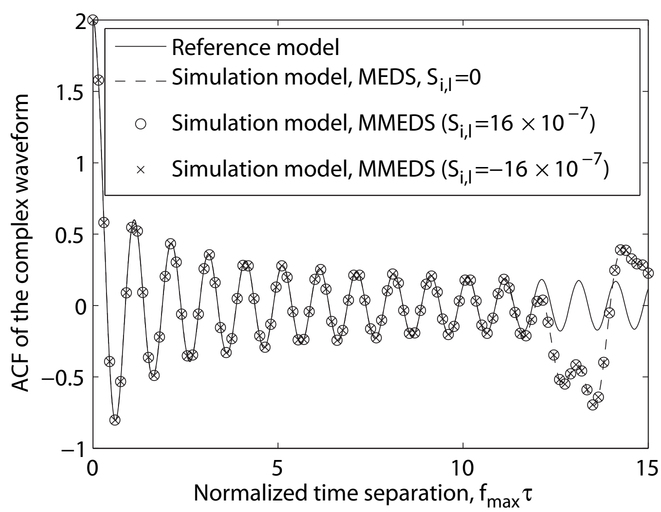

Fig. 4. The ACFs of the complex waveform for the reference model and the simulation model by using the MEDS and the MMEDS ($\sigma_0^2 = 1$, $N = 20$).

$E_{i,\ell}$. Fig. 4 shows the ACFs of the reference model $r_{\mu_\ell\mu_\ell}(\tau)$ and the simulation model $\tilde{r}_{\mu_\ell\mu_\ell}(\tau)$ for the MEDS ($S_{i,\ell} = 0$) and MMEDS ($S_{i,\ell} = \pm 16\times 10^{-7}$). In consistency with Fig. 3, the approximation $\tilde{r}_{\mu_{i,\ell}\mu_{i,\ell}}(\tau) \approx r_{\mu_{i,\ell}\mu_{i,\ell}}(\tau)$ is excellent for both the MEDS and MMEDS with the given parameter $S_{i,\ell}$ when $f_{\max}\tau \in [0, N/2]$, i.e., $f_{\max}\tau \in [0, 10]$. In Fig. 5, we present $\mathcal{L} = 4$ uncorrelated simulated fading envelopes $\tilde{\zeta}_\ell(t)$ by using the MMEDS with $\sigma_0^2 = 1$, $f_{\max} = 91$ Hz, $N = 20$, $\epsilon = 10^{-7}$, and $\ell = 1, 2, 3, 4$.

Compared with the MEDS, the proposed MMEDS provides similar approximations to the desired ACFs as long as an infinitesimal value is chosen for the quantity $S_{i,\ell}$. In other words, the performance degradation due to the introduction of $S_{i,\ell}$ can completely be neglected. On the other hand, the MMEDS does not require the increase of the numbers of sinusoids when more uncorrelated processes are produced, while the MEDS [11] needs. This promising feature of the MMEDS allows us to simulate a very large number of uncorrelated fading processes without increasing the complexity of the channel simulator.

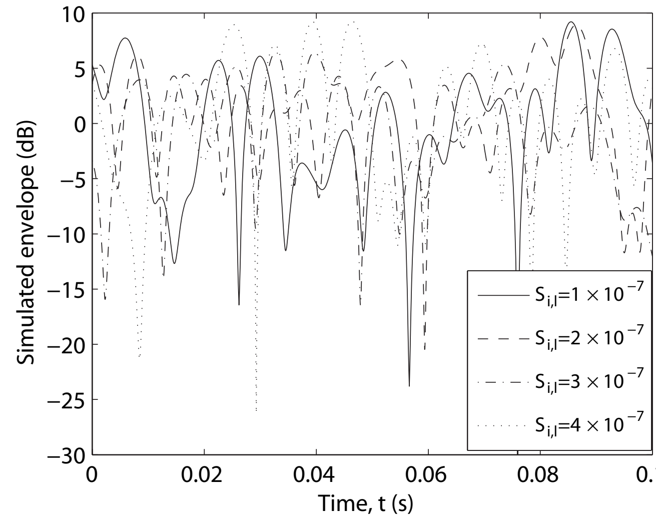

Fig. 5. Uncorrelated simulated fading envelopes $\tilde{\zeta}_\ell(t)$ (ℓ=1, 2, 3, 4) by using the MMEDS ($\sigma_0^2 = 1$, $f_{\max} = 91$ Hz, $N = 20$).

In comparison with the non-ergodic stochastic SoS channel simulators given in [6]–[9], the improved deterministic SoS channel simulator with the proposed MMEDS can provide similar good approximation of the ACFs within the specified delay range $f_{\max}\tau \in [0, N/2]$, which is of most relevance to communication systems [13]. In terms of the implementation complexity, our deterministic channel simulator is superior to the stochastic channel simulators suggested in [6]–[9] since the calculation of its statistical properties does not need the average of a large number of random trials.

It is noted that the above presented deterministic SoS channel simulator with the MMEDS can easily be extended to the generation of multiple correlated Rayleigh or even other fading waveforms, which is useful for simulating MIMO and ultra-wide band (UWB) channels [17]–[19] in a more practical way. This can be done by using a linear combination of multiple uncorrelated processes [12], [15].

IV. Conclusion

In this letter, a new parameter computation method, called MMEDS, for deterministic SoS channel simulators has been proposed to generate multiple uncorrelated Rayleigh fading processes, which are useful for the modeling of MIMO, wideband (or UWB), and diversity-combined multipath fading channels. Compared with MEDS, the MMEDS provides similar good approximations to the desired statistical properties of the reference model, while it offers a much lower computational complexity. It is simple and straightforward to apply MMEDS to generate multiple uncorrelated fading processes. The MEDS, however, demands increasing numbers of sinusoids, thus increasing channel simulator complexity. Therefore, the MMEDS is suitable for simulation of a large number of uncorrelated fading processes.

References

[1] R. H. Clarke, "A statistical theory of mobile-radio reception," *Bell Syst. Technol. J.*, vol. 47, pp. 957–1000, July/Aug. 1968.
[2] W. C. Jakes, ed., *Microwave Mobile Communications*. IEEE Press, 1994.

[3] P. Dent, G. E. Bottomley, and T. Croft, "Jakes fading model revisited," *Electron. Lett.*, vol. 29, no. 13, pp. 1162–1163, June 1993.

[4] Y. B. Li and Y. L. Guan, "Modified Jakes model for simulating multiple uncorrelated fading waveforms," in *Proc. IEEE ICC'00*, New Orleans, LA, June 2000, pp. 46–49.

[5] Y. X. Li and X. J. Huang, "The simulation of independent Rayleigh faders," *IEEE Trans. Commun.*, vol. 50, no. 9, pp. 1503–1514, Sept. 2002.

[6] A. G. Zajić and G. L. Stüber, "Efficient simulation of Rayleigh fading with enhanced de-correlation properties," *IEEE Trans. Wireless Commun.*, vol. 5, no. 7, pp. 1866–1875, July 2006.

[7] K. W. Yip and T. S. Ng, "Karhunen-Loève expansion of the WSSUS channel output and its application to efficient simulation," *IEEE J. Select. Areas Commun.*, vol. 15, no. 4, pp. 640–646, May 1997.

[8] Y. R. Zheng and C. S. Xiao, "Improved models for the generation of multiple uncorrelated Rayleigh fading waveforms," *IEEE Commun. Lett.*, vol. 6, no. 6, pp. 256–258, June 2002.

[9] Y. R. Zheng and C. S. Xiao, "Simulation models with correct statistical properties for Rayleigh fading channels," *IEEE Trans. Commun.*, vol. 51, no. 6, pp. 920–928, June 2003.

[10] M. Pätzold, *Mobile Fading Channels*. Chichester, UK: John Wiley & Sons, 2002.

[11] C.-X. Wang, M. Pätzold, and D. Yuan, "Accurate and efficient simulation of multiple uncorrelated Rayleigh fading waveforms," *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 833–839, Mar. 2007.

[12] G. L. Stüber, *Principles of Mobile Communications*. Boston: Kluwer Academic Publishers, 2nd edition, 2001.

[13] P. Hoeher and A. Steingass, "Modeling and emulation of multipath fading channels using controlled randomness," in *Proc. ITG-Fachtagung "Wellenausbreitung bei Funksystemen und Mikrowellensystemen,"* Oberpfaffenhofen, Germany, May 1998, pp. 209–220.

[14] M. F. Pop and N. C. Beaulieu, "Limitations of sum-of-sinusoids fading channel simulators," *IEEE Trans. Commun.*, vol. 49, no. 4, pp. 699–708, Apr. 2001.

[15] C.-X. Wang and M. Pätzold, "Efficient simulation of multiple cross-correlated Rayleigh fading channels," in *Proc. IEEE PIMRC'03*, Beijing, China, Sept. 2003, pp. 1526–1530.

[16] C. E. D. Sterian, C.-X. Wang, R. Johnsen, and M. Pätzold, "Rotationally invariant space-time trellis codes with 4-D rectangular constellations for high data rate wireless communications," *J. Commun. and Networks*, vol. 6, no. 3, pp. 258–268, Sept. 2004.

[17] A. F. Molisch, D. Cassioli, C.-C. Chong, S. Emami, A. Fort, B. Kannan, J. Karedal, J. Kunisch, H. G. Schantz, K. Siwiak, and M. Z. Win, "A comprehensive standardized model for ultrawideband propagation channels," *IEEE Trans. Antennas Propag.*, vol. 54, no. 11, pp. 3151–3166, Nov. 2006.

[18] D. Cassioli, M. Z. Win, and A. F. Molisch, "The ultra-wide bandwidth indoor channel: from statistical model to simulations," *IEEE J. Select. Areas Commun.*, vol. 20, no. 6, pp. 1247–1257, Aug. 2002.

[19] M. Z. Win, and R. A. Scholtz, "Characterization of ultra-wide bandwidth wireless indoor communications channel: a communication theoretic view," *IEEE J. Select. Areas Commun.*, vol. 20, no. 9, pp. 1613–1627, Dec. 2002.