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Research Article

An Analytical Prediction Model of Time Diversity Performance for Earth-Space Fade Mitigation

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Time diversity (TD) has recently attracted attention as a promising and cost-efficient solution for high-frequency broadcast satellite applications. The present work proposes a general prediction model for the application of TD by approximating the time dynamics of rain attenuation through the use of the joint lognormal distribution. The proposed method is tested against experimental data and its performance is investigated with respect to the basic parameters of a satellite link.

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1. INTRODUCTION

Several diversity reception schemes have been thoroughly investigated in the past to mitigate rain fading in fixed/broadcast satellite communication systems operating above 10 GHz. These schemes offer a significant performance improvement, especially considering the recent trend of commercial satellite networks to migrate to higher-frequency bands due to spectral and/or orbital congestion: first, from C to the Ku frequency band and, more recently, from Ku to the Ka, or even to the EHF frequency band. The established diversity techniques include [1]

(i) *site diversity* (SD), which takes advantage of the spatial characteristics of the rainfall medium by engaging two or more jointly receiving earth terminals to combat strong rain fades [2];

(ii) *orbital* (or satellite) *diversity* (OD), which takes advantage of the spatial characteristics of the rainfall medium by allowing earth stations to choose the best signal from two or more satellites [3];

(iii) *frequency diversity* (FD), which takes advantage of the spectral characteristics of the rainfall medium by employing a high-frequency band (e.g., Ka or EHF) during normal operation, and switching to a lower-frequency band (e.g., Ku or C) when the attenuation due to rain exceeds a certain threshold [4].

All the above fade mitigation techniques (FMT) produce significant diversity gains but their use is limited due to specific technical and other factors. For SD, the main limitation comes from cost considerations, since additional earth stations and terrestrial connections enabling the processing of the jointly received signals are required. In OD, limitations are imposed by the switching procedure between the satellites, as well as by the waste of satellite bandwidth. Finally, FD is rather expensive, requiring dual reception at the earth terminals.

Time Diversity (TD), is a less studied diversity alternative for satellite systems [5]. Basically, it consists of retransmitting the corrupted information at times when the channel is expected to be more favourable, that is at time spacings exceeding the channel coherence time. The basic principle of the TD technique is depicted in Figure 1. Actually, it resembles the ARQ (automatic repeat request) FMT implemented in layer 2, which falls under the general category of error correction. The difference between the two techniques is that ARQ is characterized by a fixed or random retransmission period, while TD retransmits the information after having estimated the duration of the unfavorable propagation phenomenon. Clearly, the performance of the TD technique is closely related to the time period selected for retransmission, which ranges from a few seconds to several hours. One of its main advantages when compared to other diversity

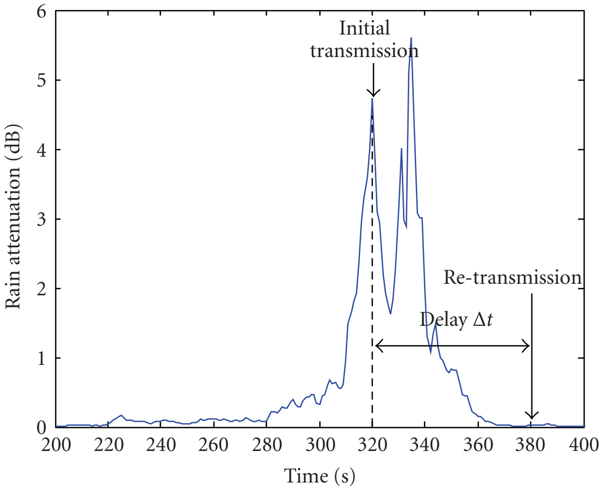

FIGURE 1: Application of the TD technique.

techniques is that TD does not require additional equipment or complicated synchronization procedures, since it involves only a single satellite link and a single reception unit. This renders the TD option cost efficient. However, the application of the TD technique is restricted to delay-tolerant applications, such as video-on-demand or multimedia and data transfer, and seems particularly attractive for broadcasting services.

Given that only a few similar models exist in the open literature (briefly outlined in Section 2), usually derived from measurements in specific regions, the present paper proposes a physical prediction model for the performance estimation of TD. The model, detailed in Section 3, relies on the assumption that the joint statistics of rain attenuation at both the initial and the retransmission instants follow the lognormal distribution. In Section 4, the prediction model is tested against TD experimental data and the main parameters influencing its performance are discussed.

2. RELATED MEASUREMENT AND MODELING ACTIVITIES

One of the first TD measurement campaigns was carried out for the equatorial region of Malaysia using a satellite beacon receiver at 12 GHz to record data from a MEASAT geostationary satellite. Apart from presenting the analysis of the 20-month data, an empirical exponential model to fit the cumulative distribution of TD was developed [6]. This distribution is defined by means of the exceedance probability

$$\Pr\{A_{\mathrm{TD}}(\Delta t) > a\} = 1 - \Pr\{\min(A(t), A(t+\Delta t)) \leq a\}, \tag{1}$$

where $A(t)$ is the sample of the rain attenuation stochastic process at time t, $A_{\mathrm{TD}}(\Delta t)$ denotes the attenuation that a TD system with a retransmission time of Δt is subjected to, and a is the fade margin. All attenuation quantities are expressed in dB. Furthermore, TD measurements from the South of England in the V frequencies bawd were reported in [7] using ITALSAT beacon data. The duration of this measurement campaign has been three years. Valuable insight on TD both through experimental data and empirical modeling for the area of Japan is given in [8], which includes eight years of attenuation data at 20 GHz. The relationship between TD gain, time delay, and time percentage was approximated by a function similar to the one proposed by the ITU-R Recommendation [9, page 618] for single site rain attenuation prediction. Note that the TD gain for the $p\%$ time percentage is given by the difference

$$G_{\mathrm{TD}}(\Delta t;\, p\%) = A_{\mathrm{TD}}(\Delta t = 0;\, p\%) - A_{\mathrm{TD}}(\Delta t \neq 0;\, p\%). \tag{2}$$

Results of the data processing for TD from the ITALSAT geostationary satellite were presented in [10]. The data were collected at 19 GHz in Italy and at 12, 20, 30, 40, and 50 GHz in Belgium over an observation period of six years. The authors in [10] assume the bivariate lognormal distribution to model the joint statistics of two attenuation random variables $A(t)$, $A(t+\Delta t)$ separated by a time delay of Δt. The correlation between these random variables in the time domain is assumed to follow the same distribution as the corresponding spatial correlation function employed in SD. This is taken into account by simply replacing the site separation distance with the TD delay. Finally in [11], a statistical assessment of TD is presented by simulating rain attenuation time series from rain rate data with the synthetic storm technique (SST) in the frequency range 10–100 GHz. The rain rate databank spans over a period of seven years.

3. PROPOSED TD MODEL

To simplify the notation, the rain attenuation random variables corresponding to the first and the second transmission of the same signal are here after denoted by A_1 and A_2, respectively. The starting point of the proposed approach is the assumption that the two samples $A_1 = A(t)$ and $A_2 = A(t+\Delta t)$ of the rain attenuation random process follow the lognormal distribution. Based on this hypothesis, it can easily be shown that the exceedance probability given by (1) may also be determined by

$$P_{\mathrm{TD}} = \Pr(A_1 > a,\, A_2 > a) = \iint_a^\infty p_{A_1A_2}(A_1, A_2)\, dA_1\, dA_2, \tag{3}$$

where $p_{A_1A_2}(A_1, A_2)$ is the joint probability density function (pdf) of $A(t)$ and $A(t+\Delta t)$. The above joint pdf is assumed to follow the bivariate lognormal distribution. The exceedance probability of a single transmission is (setting for simplicity $A = A(t)$)

$$\Pr(A_1 > a) = \int_a^\infty p_A(A)\, dA = \frac{1}{2}\operatorname{erfc}\left(\frac{\ln a - \ln A_m}{\sqrt{2}S_a}\right), \tag{4}$$

where $p_A(A)$ is the lognormal pdf, A_m and S_a are the mean value and the standard deviation of the corresponding normal random variable $\ln A$, and $\operatorname{erfc}(x)$ is the complementary error function (4) [3]. Based on the transformation

$$U = \frac{\ln A - \ln A_m}{S_a}, \tag{5}$$

the exceedance probability given by (4) is expressed as a function of the normalized attenuation U

$$\Pr(U > u) = \frac{1}{2}\operatorname{erfc}\left(\frac{u}{\sqrt{2}}\right). \tag{6}$$

Assuming that long-term rain attenuation measurements are available in the form of attenuation probability pairs, (A_i, P_i), $i = 1, \ldots, N$, where N is the number of available data pairs, the statistical parameters A_m and S_a may be evaluated by first reversing (6) to obtain

$$U_i = \sqrt{2}\,\operatorname{erfc}^{-1}(2P_i), \quad i = 1, \ldots, N. \tag{7}$$

Since U_i also satisfy (5), the following set of equations is obtained:

$$U_i = C_1 Z_i + C_2, \quad i = 1, \ldots, N, \tag{8}$$

where

$$\begin{aligned} Z_i &= \ln A_i, \\ C_1 &= S_a^{-1}, \\ C_2 &= -\ln A_m / S_a. \end{aligned} \tag{9}$$

Since U_i and Z_i are related through the linear relationship (8), a least-squares regression procedure may easily lead to the evaluation of the coefficients C_1 and C_2 and, then, to A_m and S_a. Since to obtain (4) and (6) the unconditional lognormal distribution is adopted, in the calculations only values of A_i higher than a minimum 0.5 dB threshold are taken into account. Also, in case local measurements are not available, the statistical parameters A_m and S_a may be calculated applying the procedure, summarized in (6)–(9), to the rain attenuation model of the ITU-R Recommendation [9, page 618].

Returning to the bivariate case and adopting for both random variables A_1 and A_2 the transformation (5), two normal random variables come up, namely, U_1 and U_2, each with zero mean and standard deviation equal to 1. Their joint pdf is given by

$$\begin{aligned} &P_{U_1 U_2}(U_1, U_2) \\ &\quad = \frac{1}{2\pi\sqrt{1-\rho_n^2(\Delta t)}} \exp\left\{ -\frac{1}{2\left(1-\rho_n^2(\Delta t)\right)} \right. \\ &\qquad\qquad \left. \cdot \left(U_1^2 + U_2^2 - 2\rho_n(\Delta t) U_1 U_2\right) \right\}, \end{aligned} \tag{10}$$

where the normalized time correlation coefficient ρ_n is defined by [12, 13]

$$\rho_n(\Delta t) = \frac{\exp\left(S_a^2 \exp\left(-d_A |\Delta t|\right)\right) - 1}{\exp\left(S_a^2\right) - 1}. \tag{11}$$

It should be emphasized at this point that the critical dependence of $p_{U_1 U_2}(U_1, U_2)$ and of the subsequent results on Δt is expressed by the correlation coefficient, which is a function of Δt.

The parameter d_A [s^{-1}] is the *dynamic parameter of rain attenuation* (also referred to as *beta* in the literature) describing the temporal variation of the rain attenuation process. A comprehensive investigation on how to calculate d_A based on electrical, geometrical, and climatic characteristics of the link is carried out in [14].

Based on Bayes' theorem, (10) may be expressed in terms of its marginal and conditional pdfs

$$p_{U_1 U_2}(U_1, U_2) = p_{U_2}(U_2) \cdot p_{U_1 | U_2}(U_1, U_2), \tag{12}$$

where

$$\begin{aligned} &p_{U_1 | U_2}(U_1, U_2) \\ &\quad = \frac{1}{\sqrt{2\pi\left(1-\rho_n^2(\Delta t)\right)}} \exp\left\{ -\frac{\left(U_1 - \rho_n(\Delta t) \cdot U_2\right)^2}{2\left(1-\rho_n^2(\Delta t)\right)} \right\}, \end{aligned} \tag{13}$$

and $p_{U_2}(U_2)$ is the normal pdf. Upon replacing (12), (13) into (3), the final expression for the joint exceedance probability of the two rain attenuation random variables separated in time by Δt comes up

$$P_{\mathrm{TD}} = \frac{1}{2}\int_u^\infty p_{U_2}(U)\operatorname{erfc}\left(\frac{u - \rho_n(\Delta t) U}{\sqrt{2\left(1-\rho_n^2(\Delta t)\right)}}\right) dU. \tag{14}$$

4. PERFORMANCE EVALUATION

Next, a first attempt to validate the TD statistical model based on the bivariate lognormal distribution is carried out for a variety of measured data related to various climatic zones and for links of various electrical and geometrical characteristics. The measured results for TD are simply reproduced from the open literature, as briefly outlined in Section 2.

The statistical parameters of the lognormal distribution A_m and S_a required for the application of the proposed model are obtained by fitting the experimental data of the exceedance probability concerning the single transmission. The dynamic parameter d_A is determined following the methology presented in [14]. The parameters employed in the following figures are given in Table 1.

In Figure 2, TD curves for data originating from measurements reported in [7] for Sparsholt, UK, together with curves obtained applying the proposed model are depicted. A very good convergence is observed between the two sets of curves demonstrating the validity of the proposed model.

In Figure 3, the results of the proposed model are compared to single transmission TD experimental results from Kuala Lumpur, MLA [6]. The deviation observed in Figure 3 between the appropriately modified lognormal pdf and the curves depicting the measurement is mainly due to the failure of the lognormal model to represent rain attenuation in subtropical and tropical regions of the Earth, where the gamma distribution exhibits an improved prediction performance [15].

On the other hand, the overall performance of the proposed TD model depends critically on the value selected for the dynamic parameter d_A. Although in Figures 2 and 3 the evaluation of d_A was based on the analytical methodology described in [14], there are several suggestions for a global

Table 1: Parameters employed.

Experiment	Frequency of operation to	Elevation angle	A_m	S_a	d_A
Sparsholt, UK	49.5 GHz	29.9°	1.1845	0.9359	$2.1 \cdot 10^{-4}\ \mathrm{s}^{-1}$
Kuala Lumpur, MLA	12 GHz	77.43°	0.03219	1.8791	$1.4 \cdot 10^{-4}\ \mathrm{s}^{-1}$
Spino d' Adda	19 GHz	30.6°	0.11456	1.3352	$1.0 \cdot 10^{-4}\ \mathrm{s}^{-1}$

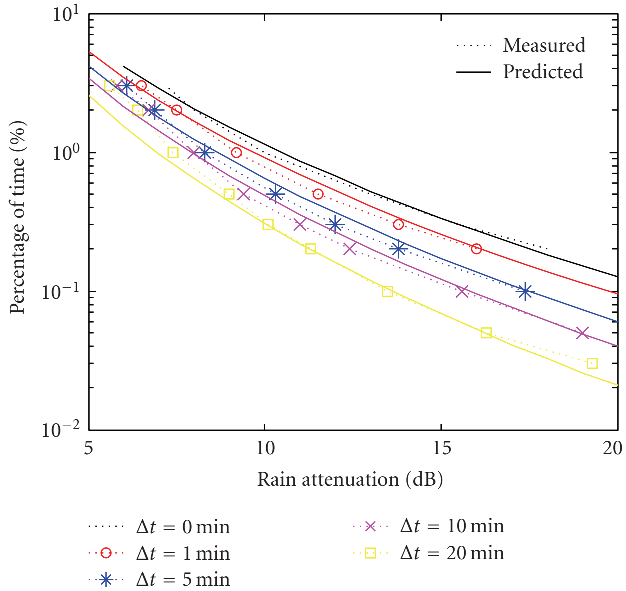

Figure 2: Performance comparison of the proposed model and measured data from a TD system operating at 50 GHz in Sparsholt, UK.

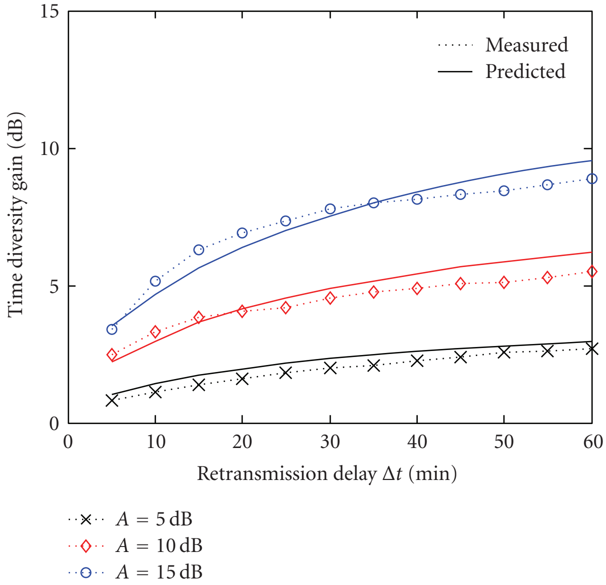

Figure 4: Proposed model and measured data in terms of time diversity gain for a TD system operating at 19 GHz in Spino d' Adda, IT.

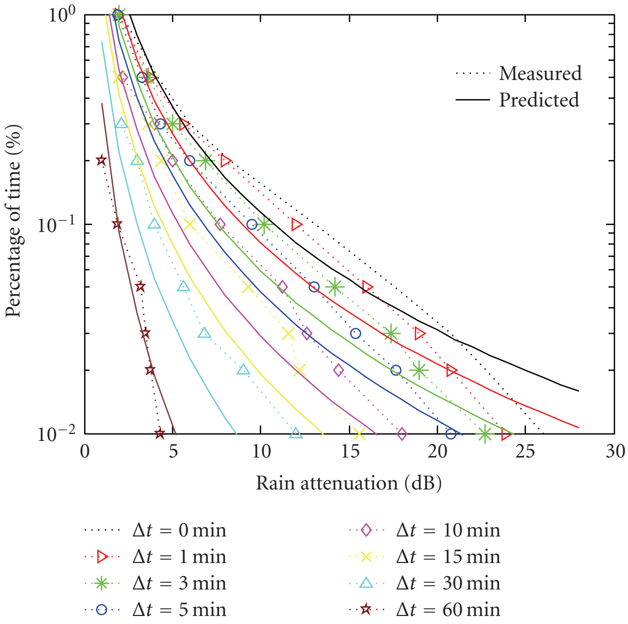

Figure 3: Performance comparison of the proposed model and measured data from a TD system operating at 12 GHz in Kuala Lumpur, MLA.

value of this parameter in the range $3.16 \cdot 10^{-4}\ \mathrm{s}^{-1} \leq d_A \leq 3.16 \cdot 10^{-3}\ \mathrm{s}^{-1}$. Furthermore, after testing experimental data from the OLYMPUS and ITALSAT campaigns, the authors in [16] suggest that a rough estimate of $d_A = 10^{-4}\ \mathrm{s}^{-1}$ can be used in North western European regions for elevation angles between 25° and 38° and frequencies between 12 GHz and 50 GHz. This value has been adopted to determine the TD gain as a function of the retransmission delay Δt in the area of Spino d' Adda, IT. TD gain curves adopting and applying the proposed model have been plotted in Figure 4. A very satisfactory convergence between the experimental values and those of the proposed model is observed, demonstrating the validity of the proposed model.

5. CONCLUSIONS

The present paper proposes a general TD prediction method based on the joint correlated bivariate lognormal distribution in the time domain. The correlation function proposed depends critically on the dynamic parameter of rain attenuation. The proposed model exhibits a very satisfactory convergence to experimental data originating from temperate climatic regions.

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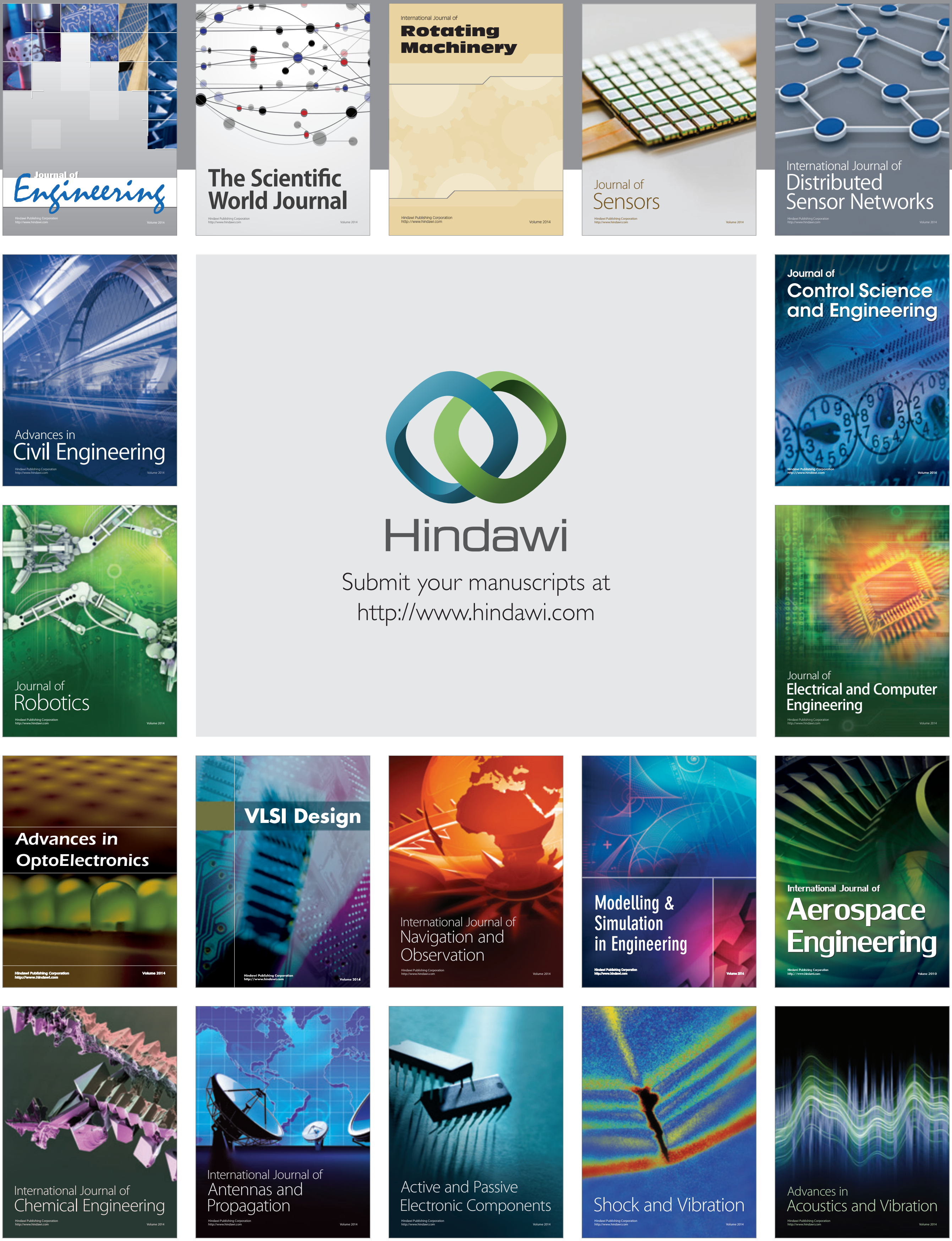

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