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FUTURE NETWORKS: 5G AND BEYOND

Statistical study of the matching properties and radiation pattern distorsion of high density randomly distributed dipoles
Étude statisque de l'adaptation et de la distorsion du diagramme de rayonnement des dipôles couplés aléatoirement répartis

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Abstract:

A statistical analysis of the coupling in a set of thin and thick randomly distributed dipoles is presented. The reflection coefficient and the radiation pattern of surrounded dipoles are calculated for a few loads of the surrounding dipoles. The cumulative distributed functions are presented for different dipole densities.

Résumé:

Une analyse statistique du couplage d'un ensemble de dipôles fins et épais aléatoirement répartis est présentée. Le coefficient de réflexion ainsi que le diagramme de rayonnement des dipôles environnés sont calculés pour quelques valeurs de charge sur les dipôles environnants. Les fonctions de répartition sont présentées pour différentes densités de dipôles.

1 Introduction

UHF RFID (Radio Frequency IDentification) technologies have a long established role for tracking and identification of objects and persons. With the growth of the Internet of Thing (IoT), the RFID technology becomes more pervasive and omnipresent. In some applications the density of RFID tags is high, this can give rise to an important electromagnetic coupling between tag antennas which modifies antenna's key parameters, i.e. matching properties and radiation pattern. These electromagnetic modifications can alter and degrade the communication links between devices, e.g. reduced read-range or read-rate.

Despite an initial description of the mutual coupling between RFID tags [1], the statistical modelling of the impact of the mutual coupling for high densities of RFID tags is still a new topic [2]. In these series of research studies, we assume that a dipole-like RFID tag antenna can be modeled by a simple wire dipole antenna. Consequently, we use the IEMF (Induced Electromotive Force) technique [3] and we extend this technique to estimate the impedance matrix of a set of thin dipoles in any orientation and position in a plane [4]. Using this impedance matrix we can calculate the input impedance (or reflection coefficient) and the radiation pattern of a surrounded dipole.

This article aims to study statistically the group behaviour of a set of randomly distributed thin dipoles and to compare the results with the statistical behaviour of thick dipoles for different density and load of surrounding dipoles.

2 Statistical assessment

In order to proceed to the statistical assessment, the same number of half-wave dipoles are distributed randomly in zOy plane over a surface of $n\lambda \times n\lambda$ as shown in figure 1. The observation point is in far-field and located by θ and φ angles. In this study, the experimental design consists in 10 identical thin and thick dipoles distributed over surfaces of dimensions $4\lambda \times 4\lambda$, $3\lambda \times 3\lambda$, $2\lambda \times 2\lambda$ and $1\lambda \times 1\lambda$. For each density, 200 random configurations have been generated using Monte Carlo method, which corresponds to 2000 samples. This number of samples has been chosen according to the convergence of the mean, the variance and the coefficient of variation for the worst case of the largest distribution surface.

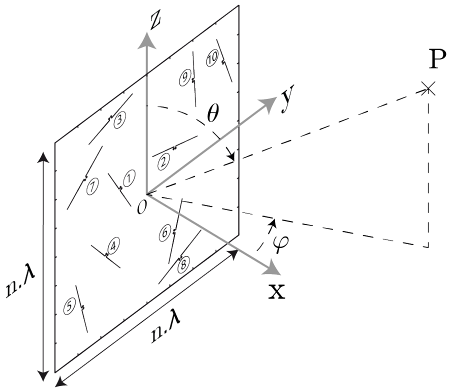

Figure 1 – A generated random configuration of dipoles and the observation point

2.1 Reflection coefficient

In order to statistically assess the mismatch of a surrounded dipole in different random configurations, the reflection coefficient $\Gamma_{\text{in}i}$ for the i^{th} surrounded dipole is defined as follows [5]:

$$\Gamma_{\text{in}i} = \frac{Z_{\text{in}i} - Z^*_{\text{ref}}}{Z_{\text{in}i} + Z_{\text{ref}}} \tag{1}$$

where the reference impedance Z_{ref} is the complex conjugate of the self-impedance of an isolated dipole. Table 1 summarizes the self impedance of thin and thick dipoles obtained by IEMF and NEC at the working frequency (892 MHz).

	IEMF	NEC
Thin dipole $\oslash 10^{-6}\lambda$	73 +j42.5	77+j44.5
Thick dipole $\oslash 10^{-3}\lambda$	-	81.5+j39.3

Table 1 – Self-impedance of dipoles

The magnitude of the input reflection coefficient (Γ_{in}) of each dipole has been calculated in dB when all other dipoles are short-circuited or matched. The cumulative distribution functions are presented in figure 2. An excellent agreement is observed between the four series of CDF obtained by extended IEMF and NEC (thin and thick dipoles). Table 2 summarizes the empirical statistical moments of the study. For each density and loading conditions, we observe that the empirical mean ($|\mu|$) and standard deviation (σ) present very close values for thin and thick dipoles, regardless of the simulation method.

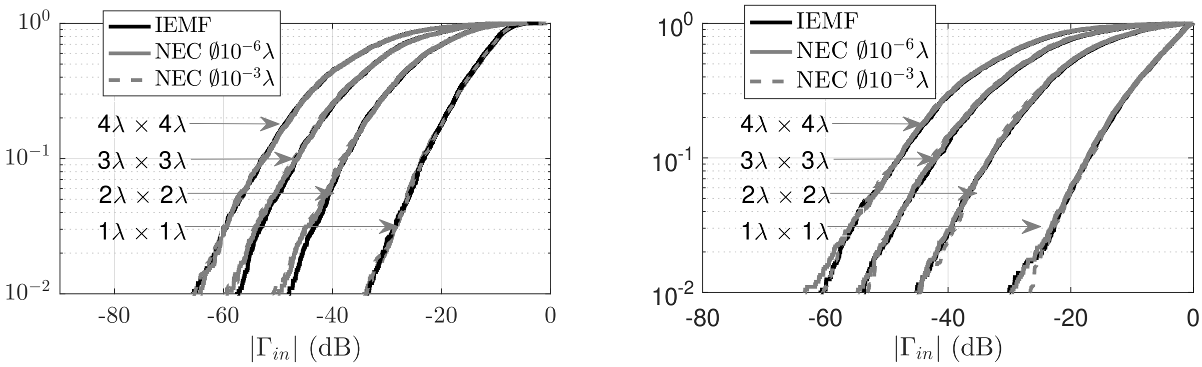

Figure 2 – CDF of the input reflection coefficient of a dipole surrounded by matched (left) and short-circuited (right) dipoles as a function of different densities obtained by extended IEMF and NEC

It important to note that neither the visual inspection of the CDF in figure 2 nor the close values of the two statistical moments in table 2 do not allow to conclude on the identical behaviour of each group of CDF. For that reason, the Kolmogorov–Smirnov test [6] associated with a level of signification equal to $\alpha = 10\%$ was used in order to check the goodness of fit. For each density and loads, the KS test has been applied to each pair of simulation conditions (e.g. IEMF and NEC $\oslash 10^{-3}\lambda$) and for each pair the test validates the goodness of fit with a high level of reliability reflected by the p-value larger than α. According to this test, we can conclude

Density	Load	Simulation condition	Statistical moments	
			$\lvert\mu\rvert$	σ
$1\lambda \times 1\lambda$	Matched	1	11.42	6.99
		2	11.50	7.05
		3	11.57	7.02
	Short-circuited	1	8.27	6.60
		2	8.33	6.62
		3	8.55	6.65
$2\lambda \times 2\lambda$	Matched	1	22.81	9.83
		2	22.94	9.80
		3	23.23	9.72
	Short-circuited	1	20.41	9.80
		2	20.59	9.79
		3	20.98	9.76
$3\lambda \times 3\lambda$	Matched	1	30.11	11.27
		2	30.26	11.20
		3	30.40	11.19
	Short-circuited	1	27.69	11.06
		2	27.94	11.12
		3	28.16	11.08
$4\lambda \times 4\lambda$	Matched	1	35.37	11.82
		2	35.55	11.88
		3	35.87	12.13
	Short-circuited	1	33.13	11.85
		2	33.37	11.94
		3	33.71	11.96

Table 2 – Statistical moments of reflection coefficient ($|\Gamma_{\text{in}}|$) of surrounded dipoles, where the numbers present the simulation condition: 1 : IEMF, 2 : NEC $\oslash 10^{-6}\lambda$ et 3 : NEC $\oslash 10^{-3}\lambda$.

that the statistical behaviour of the thick and thin dipoles are the same even if the intrinsic values of their input impedances and thus their reflection coefficients are quite different.

Figure 2 also shows that for a given mismatch level, the number of dipoles presenting better matching properties increases as the distribution surface increases (or the density decreases). In the case of short-circuit load the percentage of dipoles presenting a smaller reflection coefficient than $|\Gamma_{\text{in}}|$ =–10 dB, is equal to 33% for the highest density ($1\lambda \times 1\lambda$) and reaches 99.6% for the lowest density ($4\lambda \times 4\lambda$) as presented in the table 3. It is also observed that for a given density of tags, the loads of the surrounding dipoles have a very important influence on the reflection coefficient of a surrounded dipole. For $1\lambda\times1\lambda$ surface, the percentage of dipoles having $|\Gamma_{\text{in}}| \leqslant -10$ dB increases from 33% with short-circuited surrounding dipoles to 75% with matched surrounding dipoles.

Load	$1\lambda \times 1\lambda$	$2\lambda \times 2\lambda$	$3\lambda \times 3\lambda$	$4\lambda \times 4\lambda$
Matched	75.35%	96.65%	98.7%	99.6%
Short-circuited	32.7%	84.05%	94.55%	97.3%

Table 3 – Percentage of matched dipoles

2.2 Radiation pattern

A method for estimating the radiation pattern of a driven antenna surrounded by a set of dipoles was initially developed in [7]. This method consists in determining the radiation pattern of a driven dipole by using the field radiated by each isolated element and the impedance matrix of the network. For a given direction of observation, the radiation field of a surrounded dipole is compared to the radiation field of the same dipole when isolated. For this direction, we calculate the ratio between these two field quantities as follows:

$$g_{\text{norm}} = \frac{|E_{\text{surrounded}}|}{|E_{\text{isolated}}|} \tag{2}$$

where $E_{\text{surrounded}}$ is the electric field of the surrounded dipole and E_{isolated} is the eclectric field of the same dipole, when this latter is isolated.

According to the position and the orientation of the surrounded dipole and the density and the load of surrounding dipoles, the mutual coupling may have a positive impact on dipole radiation ($g_{\text{norm}} > 1$), or may degrade the radiation of the isolated dipole ($g_{\text{norm}} < 1$). Figure 3 shows the cumulative distribution functions of g_{norm} for the surrounded dipoles whose radiation is degraded compared to the radiation of the isolated dipole at the observation point $\theta = 90°$ and $\varphi = 0°$. We can see that for a threshold of $g_{\text{norm}} \leq 0.8$ which represent a degradation higher than 20%, by increasing the density of the dipoles the percentage of dipoles having g_{norm} less than or equal to the threshold also increases. We can also observe in table 4 that the load of the surrounding dipoles has an important influence on the percentage of the degraded dipoles.

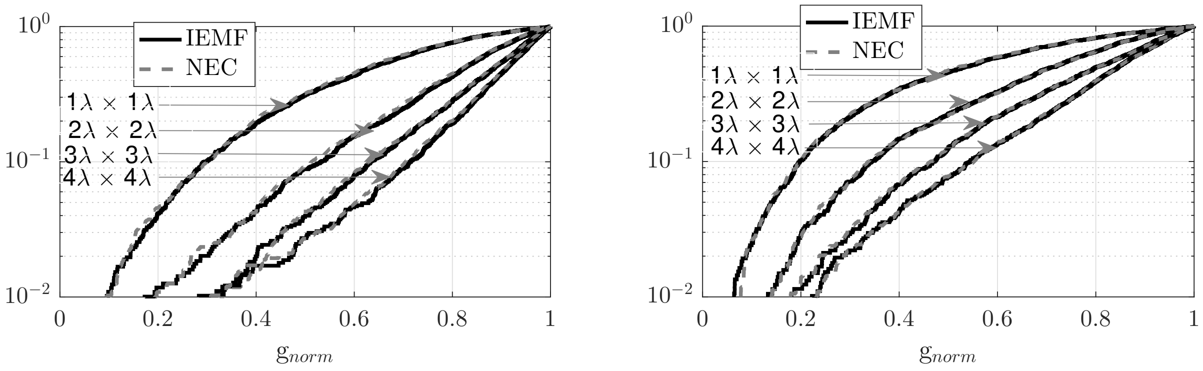

Figure 3 – CDF of g_{norm} for the set of surrounded dipoles whose radiation is degraded compared to the isolated dipole in the presence of matched (left) and short-circuited (right) dipoles as a function of different densities obtained by extended IEMF and NEC

Load	$1\lambda \times 1\lambda$	$2\lambda \times 2\lambda$	$3\lambda \times 3\lambda$	$4\lambda \times 4\lambda$
Matched	78%	44%	29%	20%
Short-circuited	82%	65%	49%	40%

Table 4 – Percentage of dipoles presenting a degradation higher than 20%

3 Conclusion

A set of tag antennas has been modeled by thin arbitrary distributed and oriented dipoles. In this paper, the input reflection coefficient and the radiation pattern of a surrounded dipole are calculated for different configurations of surrounding dipoles. The statistical assessment provides interesting conclusions about the percentage of mismatched dipoles as well as the distorted radiation pattern in the direction of the reader. The influence of the density, the loads and the thickness of the dipoles on the results have also been quantified. The results of the statistical study show also a similar group behaviour between thin and thick dipoles.

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