Performance Evaluation of Passive Tag to Tag Communications

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ABSTRACT In the context of the UHF (Ultra High Frequency) passive RFID (Radio Frequency Identification) technology, recent works have proposed a new paradigm demonstrating the possibility to perform short distance tag to tag (T2T) communications. This paper presents a study that focuses on the performance evaluation of T2T systems. Without loss of generality as to the methodology followed, dipole antennas are considered here (assumed ideal in the theoretical part, then printed for the rest of the study). The results obtained show that the modulation depth, which can be considered as an evaluation metric for the T2T systems, is strongly impacted by three main parameters: the switching impedances (here chosen as short-circuit and open-circuit); the geometrical configuration constituted by the two tag antennas forming the T2T system; and also, the position of the external source on which the backscatter communication relies. As the modulation depth is very sensitive to these three parameters, which are more or less directly related, it is very difficult to predict the communication quality for a given configuration. For example, when the two tags are in parallel and the source is symmetrically positioned, the modulation depth shows a decreasing trend by oscillating when the distance between the tags increases from 0.1 λ to 1 λ (λ being the wavelength): with values going from 70% to less than 5%. As a consequence, from a very complete set of scenarios considered, the presented study helps to illustrate and explain the interactions of these parameters and their impact on the modulation depth. And at the same time, the paper provides guidelines for defining the specifications of such a system based on quantified results. The set is completed by introducing the BER (Bit Error Rate) as an evaluation metric by considering then a more complete T2T system (for instance listener tag including a non-coherent envelope detector).

INDEX TERMS Backscattering, passive tags, tag to tag communications, UHF RFID.

I. INTRODUCTION

The backscatter technique was first introduced by Stockman in 1948 [1] and quickly became the key technology for low-power wireless communication systems with a broad range of scenarios such as tracking devices, remote switches, low cost wireless sensor networks and, more generally, the Internet of Things (IoT) [2]-[4]. The main idea is to exploit the waves provided by a distant RF source (that can be dedicated or ambient) for backscattering, for instance reflecting more or less the RF signal, and so, to transmit the information by load modulation.

Ambient backscatter [5] has been emerging as a promising technology for low-energy communication systems. In this particular communication scenario, the backscatter transmitter sends the data by the means of an incoming electromagnetic (EM) field broadcasted by ambient RF sources, e.g. TV (television) or FM (Frequency Modulation) radio towers [5], Wi-Fi and even Bluetooth Low Energy [6], thereby reducing the system’s power consumption.

Generally, the RF signals which are modulated by the backscatter transmitter usually have low levels [7]. Consequently, from the communication system point of view, the
improve the communication range between the UHF RFID impacted [13].

modulation states and implicitly the modulation depth is communication performance since the difference between the communication range are modified. Consequently, the antenna characteristics such as the tag's close vicinity antennas. Moreover, the tag's close vicinity also reliability. Consequently, a better understanding of the scenarios demands to increase the communication range and was established. However, the tag to tag (T2T) application (for instance 0.076 λ at 915 MHz, with λ is the wavelength) was established. However, the tag to tag (T2T) application scenarios demands to increase the communication range and also reliability. Consequently, a better understanding of the wireless propagation principles and of the coupling between the tag’s antennas are necessary.

The T2T communication performance is dependent on the tag’s relative position. Moreover, the tag’s close vicinity creates an important EM coupling between their respective antennas. Consequently, the antenna characteristics such as the radiation pattern or the input impedance are modified. These modifications have an impact on the T2T’s communication performance since the difference between the modulation states and implicitly the modulation depth is impacted [13].

A handful of works have been conducted in order to improve the communication range between the UHF RFID tags. In [14], a novel multi-phase backscattering technique is proposed to suppress phase cancellation and demonstrated the capability of T2T link to operate at longer distances (above three meters) in the presence of an excitation signal strength of only −20 dBm. In [15], the design of a power efficient demodulator is investigated to increase the T2T communication range with a modulation depth higher than 75%. In [16], a theoretical evaluation framework has been proposed as a tool allowing the performance evaluation of T2T radio links in terms of Bit Error Rate (BER). This study was extended by [17] which introduces analytical expressions for the error probability in the case of 2-ASK (Amplitude Shift Keying) modulation and considering that the LT consists of a coherent or non-coherent receiver demodulator.

In this paper, the impact of the relative position between two identical tags, which form the T2T system, as well as the impact of the position of the external source, which enables the communication between the tags by backscattering, are studied in depth. The objective is to evaluate the performance of T2T communication as a function of these two parameters by considering several possible scenarios.

The rest of the paper is organized as follows. Section II focuses on the LT’s input impedance and highlights the impact of the mutual coupling between the tags. On the one hand, the relative position between the LT and the RT (for instance their separation distance, their orientation with respect to each other, their alignment), and on the other hand, the impedance load of the RT (considered here as short-circuited and open-circuited) are examined. The presented study is divided into two parts: the first one considers an ideal case (infinitely thin dipoles) and presents results based on theory and simplified simulations; the second one considers a practical case (printed dipoles) and presents results based on simulations and measurements. Section III evaluates the T2T system using the modulation depth as a metric. The impact on the modulation depth of three types of RT arrangement (for instance parallel, tilted, and staggered with respect to the LT) and the position of the external source are studied in detail from simulations. The influence of the LT’s input impedance and the voltage gain on the modulation depth are particularly discussed and analysed in order to well-understand the observed variability on the modulation depth. In addition, the performance evaluation is extended by considering a system view of the T2T communications and the classical metric in digital communications, namely the BER. Finally, Section IV draws the conclusion and perspectives.

II. IMPACT OF THE MUTUAL COUPLING ON THE INPUT IMPEDANCE OF THE LISTENER TAG

In the T2T communications, the system formed by the two tags can be represented as an array of two coupled antennas. RT sends its information by switching its antenna’s load on two different impedances. The choice of these two impedances will have an important impact on the T2T system performance. In this study, we consider them as a short-circuit (SC) and an open-circuit (OC), without loss of generality.
as to the methodology followed and in agreement with the articles that have presented preliminary results on the subject treated. Depending on the load impedance (SC or OC) of the RT, the input impedance $Z_{in}$ of the coupled antenna array, which corresponds to the impedance seen between the LT terminals, will be different. We will note $Z_{in,ON}$ when the RT load is an SC and $Z_{in,OFF}$ when the RT load is an OC; and in a more condensed form: $Z_{in,ON/OFF}$. In addition, $Z_{in}$ will obviously also depend on the relative arrangement between the two antennas.

The following study in this section aims at investigating precisely this phenomenon, first in the case of “ideal” antennas (infinitely thin dipoles) in theory and simulation, and then in the case of printed dipole antennas in simulation and measurements. It should also be noted that the load impedance of the RT and the relative arrangement between the two antennas will also have an important impact on the voltage gain. Note that, the voltage gains are calculated from the far-field gains of the coupled antenna array (gain which will be denoted by $G_{ON}$ and $G_{OFF}$ respectively for a SC and an OC load; and in a more condensed form: $G_{ON/OFF}$); this will be detailed and clarified in section III.

A. THEORETICAL STUDY OF THE MUTUAL IMPEDANCE FOR INFINITELY THIN DIPOLES

In this section, the objective is to derive the analytical expression for the mutual impedance of the two identical coupled antennas regardless of their relative position. For this purpose, the two tag antennas are assumed to be ideal dipole antennas (called infinitely thin dipoles) and for their study the IEMF method is then applied as in [18] and [19], with the induced currents assumed to be sinusoidal.

As shown in Figure 2, the two antennas are placed in close proximity to each other, and more precisely are located at ($x_{RT}$, $y_{RT}$) and ($x_{LT}$, $y_{LT}$) respectively. The RT tilt’s angle with respect to y axis is $\theta_{RT}$. The distance between the two tags is given and considered as fractions of the wavelength. Under these considerations, the mutual impedance can be calculated by using (1).

$$Z_{21} = \int_{\frac{1}{2}}^{1} E_{21} \sin \left( \frac{\beta}{2} \right) ds$$

(1)

where:

$$E_{21} = \frac{1}{s} (E_x s_x + E_y s_y)$$

(2)

with

$$E_x = -\frac{j \cdot 30 \cdot I_1}{dx + s_x} \left[ -e^{-j \beta r_1} \cdot \cos \alpha_1 - e^{-j \beta r_2} \cdot \cos \alpha_2 + 2 \cos \left( \frac{\beta l}{2} \right) \cdot e^{-j \beta r} \cdot \cos \alpha \right]$$

(3)

and

$$E_y = \frac{j \cdot 30 \cdot I_1}{r} \left[ 2 e^{-j \beta r} \cdot \cos \left( \frac{\beta l}{2} \right) - \frac{e^{-j \beta r_1}}{r_1} - \frac{e^{-j \beta r_2}}{r_2} \right]$$

(4)

where $E_{21}$ is the electric field intensity present at each point $s$ along RT’s dipole due to the current along LT. $l$ is length of the dipoles, $\beta$ is the wave number. The distances $r$, $r_1$ and $r_2$ are deduced from the y axes to $s$. $\alpha_1$ and $\alpha_2$ are positive angles. $s_x$ and $s_y$ are the Cartesian’s components of $s$. The following equations give the geometrical parameters corresponding to Fig. 2 to be inserted in equations from (1) to (4):

$$s_x = s \cdot \sin \theta_{RT}$$

(5)

$$s_y = s \cdot \cos \theta_{RT}$$

(6)

$$dx = x_{RT} - x_{LT}$$

(7)

$$r^2 = (dx + s_x)^2 + (y_{RT} + s_y)^2$$

(8)

$$r_1^2 = (dx + s_x)^2 + \left( y_{RT} + s_y + \frac{l}{2} \right)^2$$

(9)

$$r_2^2 = (dx + s_x)^2 + \left( y_{RT} + s_y - \frac{l}{2} \right)^2$$

(10)

Finally, the mutual impedance $Z_{21}$ is calculated by integrating the induced field $E_{21}$ with respect to an incremental distance $s$ along the RT’s dipole.

Fig. 3 presents the variation of the mutual impedance $Z_{21}$ as function of the separation distance $d$ between the two parallel thin dipoles when the RT is short-circuited. The coupling effect in terms of mutual impedance is greatest for short distances and decreases progressively in ripples as the distance increases. In particular, zero values for the real part of the mutual impedance ($R_{21} = 0 \, \Omega$) are observed for distances equal to $0.43 \, \lambda$, $0.96 \, \lambda$, $1.48 \, \lambda$ and $1.98 \, \lambda$. It should be noted that when the RT is open-circuited, there is no impact of the mutual impedance. Fig. 4 shows the evolution of the mutual impedance as a function of the RT’s antenna tilt $\theta_{RT}$ and for different spacing distances: $\frac{l}{2}$, $\frac{2l}{3}$ and $\lambda$. As expected, the spacing between the tags and their tilt changes significantly the mutual impedance $Z_{21}$. This impedance decreases while the distance $d$ between the two antennas increases. This is due to the diminution of the EM coupling between the antennas.
FIGURE 3. Real part ($R_{21}$) and imaginary parts ($X_{21}$) of the mutual impedance $Z_{21}$ as function of separation distance $d$ (normalized value) between the dipoles when the reader tag is short-circuited.

FIGURE 4. Real part ($R_{21}$) and imaginary parts ($X_{21}$) of the mutual impedance $Z_{21}$ as function of $\theta_{RT}$ tilt angle of the RT’s dipole for several separation distances $d$ (normalized value) between the dipoles when the reader tag is short-circuited.

FIGURE 5. Calculated and simulated input impedance $Z_{in}$ of the listener tag. The resistance ($R_{in}$) and reactance ($X_{in}$) are plotted as function of separation distance $d$ (normalized value) between the two infinitely thin dipoles when the reader tag is short-circuited.

and this will impact the effective EM characteristics of the system (antennas parameters such as the radiation pattern and matching properties).

It should be also noted that there are two ways to express the tilt angle of the RT’s antenna. For example, $\theta_{RT} = 45^\circ$ is the same physical configuration as $\theta_{RT} = 225^\circ$. However, the value of $Z_{21}$ is of opposite sign. This is due to the voltage reference [18]. In order to avoid confusion, $\theta_{RT}$ is defined such that it is not exceeding $90^\circ$.

Finally, the knowledge of the mutual impedance $Z_{21}$ according to the relative position of the tags allows to easily deduce the LT’s input impedance as detailed in the following section.

**B. CASE OF ELECTRICALLY THIN DIPOLES: THEORY AND SIMULATIONS**

From the above study, the input impedance $Z_{in}$ is calculated for different configurations. The theoretical results obtained are compared with the results of EM simulations, performed for this part with the free software 4NEC2 (which is based on the method of moments, MoM).

To be more precise, the two nearly coupled tags can be seen as a matrix of two antennas which are considered identical. Assuming the reciprocity between the two tag’s identical antennas, the self ($Z_{11}, Z_{22}$) and the mutual ($Z_{12}, Z_{21}$) impedances of both antennas are equal. Considering the two RT’s antenna loads ($Z_{L,ON}$ for the SC and $Z_{L,OFF}$ for the OC), the LT’s input impedance $Z_{in}$ can be written as follows:

$$Z_{in,ON/OFF} = Z_{11} - \frac{Z_{21}Z_{12}}{Z_{22} + Z_{L,ON/OFF}}$$  \hspace{1cm} (11)

The real and imaginary parts of the LT’s input impedance as function of the separation distance $d$ between the two dipoles are shown in Fig. 5 and Fig. 6, when the RT is in SC and OC mode respectively. As expected, thanks to the study of the mutual impedance, the presence of the RT in SC mode affects significantly the LT’s input impedance at short distances; and this effect decays when the separation distance between the tag’s antennas increases. The RT in OC mode has no impact on the LT’s input impedance; indeed, no sinusoidal current is generated.

Thus, as a first approximation, these two methods (for instance theoretical calculation and simulation with 4NEC2 software) allow to quickly evaluate the impact of the tags’ arrangements on the LT’s input impedance. However, they are limited and cannot consider arbitrary complex antennas. For further study and also for practical considerations, simple but realistic antennas will now be considered. Consequently, the theoretical part will not be developed, the simulation steps will be performed with a more accurate EM simulator, CST Microwave Studio (based on the finite element method, FEM), and will be compared with measurement results beforehand.
C. CASE OF PRINTED DIPOLES: EM SIMULATIONS AND MEASURES

Since commercial RFID tag antennas are often based on dipole antennas (incorporating some improvements: e.g. miniaturization techniques with the use of folded dipoles or matching techniques with an additional loop in the antenna design), for the remainder of the study including an experimental part, simple antenna dipoles, for instance printed dipoles, are considered. It is important to note that, depending on the tag’s antenna configuration considered in practice, the observed characteristics will probably be different compared to those presented here, but both the methodology and the trend of the observed behaviour remain valid.

The considered antennas of the tags are printed dipoles on FR4 material with substrate dimensions 150 mm × 10 mm and copper printed circuit tracks 134 mm × 1 mm). Fig. 8 shows the simulation models and the photos of the two closely coupled antennas in each modulation states (SC and OC) of RT. As shown by Fig. 9, each printed dipole was designed such that its self-impedance $Z_{11}$ is 50 Ω at the frequency of 868 MHz. Fig. 10 shows the reflection coefficient $S_{11}$ and a relatively good agreement between simulation and measurement results.

Finally, using this antenna for the two tags, the T2T system is built up and the LT’s input impedance is simulated and measured for the two cases considered (RT in SC mode and in OC mode). Assuming a parallel arrangement, Fig. 11 and Fig. 12 show the real and imaginary parts of the input impedance $Z_{11}$ as a function of the distance $d$ between the antennas and with respect to the two RT’s loads. The simulation results are consolidated with the experimental ones and we can observe a good agreement between the two. Moreover, it should be noted that the observed behavior is very similar to that obtained in the previous more idealistic case. In particular, the weak impact of the presence of the RT in short-circuit and on the contrary its more important impact when it is in short-circuit.

III. PERFORMANCE EVALUATION OF THE T2T COMMUNICATION SYSTEM

Based on the previous study, this section aims at evaluating the performance of T2T communication by considering a given scenario, for instance the geometrical configuration constituted by the two tag antennas forming the T2T system, and also, the position of the external source on which the
FIGURE 10. The simulated and measured reflection coefficient \( S_{11} \) of the tag’s printed dipole.

FIGURE 11. Simulated and measured input impedance \( Z_{\text{in}} \) of the listener tag. The resistance \( (R_{\text{in}}) \) and reactance \( (X_{\text{in}}) \) are plotted as function of separation distance \( d \) (normalized value) between the two printed dipoles when the reader tag is open-circuited.

backscatter communication relies. Taking up the diagram presented in Fig. 2, Fig. 7 gives an updated illustrated representation with the printed dipoles and the external RF source which emits the continuous wave, clarifying and completing the important parameters considered for the different configurations envisaged (including \( d \) the distance between the two tags, \( \theta_{RT} \) the title angle of RT, and \( \theta_s \) the angle defining the source position relative to the \( z \) axis in the \( xOz \) plane).

It is worth noting that, so far, we have considered for the illustrations the case where the tags are aligned. Using the same method, further illustrations of the variation of LT’s input impedance can be found in [20] for cases where the tags are not aligned but tilted and staggered, considering RT in SC mode and OC mode. In this section, the presented results will be more complete and will illustrate the different configurations considered. Note also that throughout the section, we have been mindful of practicalities and have been careful not to present unrealistic scenarios that would involve the tags overlay (for example, in Fig. 13, when we assumed an \( \theta_{RT} \) angle of 20° we made sure that at the smallest distance considered, there was no contact between the tags).

A. MODULATION DEPTH AS METRIC OF COMMUNICATION PERFORMANCE

The modulation depth is used as an evaluation metric. This parameter plays a particularly crucial role in the communication performance of T2T systems which rely on 2-ASK modulations. Indeed, on the one hand, these systems are very sensitive to noise because the signals involved are of low to very low energy, and on the other hand, in order to keep the passive character of the tags, the demodulator is often a simple envelope detector. Thus, the greater the modulation depth (for instance the greater the separation of information levels), the more robust the communication will be to channel noise and the information will be easy to detect.

Recall that the principle of a T2T communication is as follows: as a result of the RT’s commutation between the two loads, the input voltage at LT toggles between two levels, here noted \( A_{\text{ON}} \) and \( A_{\text{OFF}} \), corresponding to a 2-ASK modulation. Besides the two levels \( A_{\text{ON}} \) and \( A_{\text{OFF}} \) are function of the LT’s antenna input impedance \( Z_{\text{in,ON/OFF}} \) and the two antennas voltage gain \( G_{\text{ON/OFF}} \), as described in equation (12).

\[
A_{\text{ON/OFF}} = A_{\text{in}} \cdot G_{\text{ON/OFF}} \left| 1 - \left( \frac{Z_{\text{in,ON/OFF}} - Z_0}{Z_{\text{in,ON/OFF}} + Z_0} \right) \right| \quad (12)
\]

where \( A_{\text{in}} \) is the input voltage at LT delivered by the external source and \( Z_0 \) the reference impedance which was considered 50 \( \Omega \), without loss of generality.

And finally, the modulation depth \( D \) is defined in terms of the two voltage levels \( A_{\text{ON}} \) and \( A_{\text{OFF}} \), as follows:

\[
D = \frac{|A_{\text{ON}} - A_{\text{OFF}}|}{\max(A_{\text{ON}}, A_{\text{OFF}})} \quad (13)
\]
TABLE 1. Summary of T2T performance in terms of modulation depth for parallel arrangement between tags in function of the separation distance and comparison with literature results.

| Reference | Substrate type | Frequency (MHz) | Source position | Separation distance ($\frac{\lambda}{2}$) |
|-----------|----------------|-----------------|-----------------|------------------------------------------|
| 12        | Rogers 4003C   | 915             | Supposed at 90° | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| 13        | Unknown        | 870             | Supposed at 90° | 58% | 42% | 39% | 35% | 23% | 19% | 15% | -  | -  | -  | -  |

This article. FR4 868 90° 34% 43% 33% 18% 13% 34% 3% 21% 16% 6%

It should be noted that, for the study presented, the ON and OFF states refer to the load impedances of the RT, for instance SC and OC respectively.

In order to study the influence of the two tags’ relative position on the modulation depth $D$, different scenarios are simulated. Note that for all figures, the modulation depth will be expressed as a percentage and noted as Modulation depth (%).

First, the RF source is fixed, perpendicular to the plane containing the two tags ($\theta_s = 0°$). Fig. 13 presents the evolution of the modulation depth $D$ as function of the distance $d$ between the tags and three types of RT arrangement: RT is parallel to LT; RT is tilted by $\theta_{RT} = 20°$; RT is staggered by $0.2\lambda$. As a priori expected, the maximum modulation depth is obtained for short distances between the tags. It is noticeable that the higher modulation depth is obtained with the parallel arrangement. Globally, the modulation depth decreases similarly by the distance $d$ and those for the considered three configurations (for instance parallel, tilt, stagger).

It should be noted that the lowest values of the modulation depth ($D \leq 5\%$) are observed for the distance $0.4\lambda$ and $0.9\lambda$. This result is coherent with the input impedance shown in the Fig. 12. Indeed, for these two distances where the mutual coupling is negligible, the input impedance $Z_{in}$ is approximately equal to $Z_{11}$ for the SC and OC modes. As a consequence, the two states are the same and the modulation depth is also zero. Fig. 14 shows the evolution of the modulation depth $D$ for RT tilts (with respect to a vertical position) varying from $\theta_{RT} = 0°$ to $70°$, and also, for three distances $d$ ($0.3\lambda$, $\lambda$, and $2\lambda$) between the two tags.

For these three distances, the modulation depth $D$ decreases significantly while the RT’s tilt angle $\theta_{RT}$ increases. This first set of results (Fig. 13 and Fig. 14) demonstrates the sensitivity of the T2T communication system with respect to the tags arrangement. In addition, the parallel configuration is more favourable as it maximizes the modulation depth $D$.

The study is now completed by considering changes in the orientation of the illuminating source, a parameter that also has a strong influence on the modulation depth. From the Fig. 15 to Fig. 17, the three previous scenarios are considered: RT is parallel to LT (Fig. 15), RT is staggered by $0.2\lambda$ (Fig. 16), and RT is tilted by $\theta_{RT} = 20°$ (Fig. 17). For each case, the modulation depth $D$ is illustrated as the distance between the tags (for instance the normalized distance $\frac{d}{\lambda}$ which varies between 0.1 and 1 with a step of 0.1) considering six positions of the distant RF source (for instance $\theta_s = -60°$, $-30°$, $0°$, $30°$, $60°$, $90°$). Furthermore, each considered scenario, the best case (for instance $D$ maximum for a given distance) is highlighted: the corresponding angle is noted $\theta_{opt}$. It is worth noting that this most advantageous case is not systematically when $\theta_s = 0°$. Indeed, for instance, and for the three RT’s illustrated configurations, we can remark that for $d = 0.4\lambda$ (about 14 cm at 868 MHz) the modulation depth can be increased by changing the source orientation. For the separation distances above $0.2\lambda$, the optimal angle of the source $\theta_s$ is the same for the three RT’s configurations. The minimum modulation depth $D$ is $21\%$ and is obtained for the maximal separation distance ($d = \lambda$). This set of
results also shows that a parallel arrangement between the tags will enable to maximize easily the modulation depth. Moreover, the T2T communication quality, regardless tags configuration (here, considering spacing, stagger and tilt cases), can be improved by tuning the source orientation $\theta_{opt}$ with respect to the tag’s position. The results presented in Fig. 16 to Fig. 17 confirm the fact that the external source need to change its position in the tags’ vertical plane in order to achieve $\theta_{opt}$, and thus to maximize the modulation depth whatever the tags’ relative position. Consequently, the chance that the two tags are communicating together is maximized.

In addition, all these results also show that the knowledge of the variation of the modulation depth with respect to the two tags configuration could be used, for instance, as a source of information. Indeed, the activation of T2T communication could be translated as a proper or tolerable alignment between the tags.

Finally, Table 1 highlights and compares with the literature [12], [13] the values of the modulation depth $D$ as a function of separation distance $d$ for the parallel tag arrangement when the source is oriented at $\theta_s = 90^\circ$ (and assumed to be so oriented likewise for the two references cited which do not give explicitly this information, although critical as highlighted in this work). The results we present here are taken from Figure 15. Comparing the results achieved here with those of the literature, some differences are observed especially for the distances $0.1 \lambda$, $0.6 \lambda$, $0.7 \lambda$ and $\lambda$. It should be noted that the considered antennas, as well as the employed substrates, are not the same in the three studies. If the strict decrease of the modulation depth when the distance increases may seem “natural” because the coupling between the antennas also decreases, we will see later (Section III.B) that the analysis is not so simple and must be completed because, in particular, the impact of the gain is also to be considered.

### B. ANALYSIS OF THE RESULTS AND DISCUSSION

As shown in the presented results, the modulation depth, which is a fundamental parameter impacting the T2T communication, is highly variable depending on the considered scenario (for instance the considered relative arrangement between the tags and the external source position). Indeed, the modulation depth is a function of both the LT’s input impedance and the voltage gain of the coupled dipole; and consequently, its variations are complex and very difficult to predict.

In order to illustrate more precisely the observed variability of the modulation depth, let us imagine the following scenario: the tags are arranged in parallel and separated by a distance of $0.4 \lambda$. The difference, $\Delta Z_{in}$, between the values of the LT’s input impedances when RT is open-circuited (Fig. 11) and when RT is short-circuited (Fig. 12) is nearly zero. This result is consistent because for this distance between tags, whatever the RT load, we observe that the mutual
impedance is very low \((Z_{12} = Z_{21} \approx 0 \, \Omega)\); therefore: \(Z_{in,ON} \approx Z_{in,OFF} \approx Z_{11}\) and \(\Delta Z_{in} = Z_{in,ON} - Z_{in,OFF} \approx 0 \, \Omega\).

Now, if we consider the modulation depth for this configuration in Fig. 15, we notice that it varies significantly between 4\% (worst configuration with the source at \(\theta_s = 0^\circ\)) and 54\% (best configuration with the source at \(\theta_s = -30^\circ\)). Let us then add in the analysis this effect of the position of the source. Note that the presence of the RT in short-circuit acts as a parasitic element and therefore impacts the overall radiation pattern, which is not the case when RT is in open-circuit. Fig. 18 shows the 2D radiation pattern (vertical plane) of the gain for the coupled tags (always considered as arranged in parallel with a distance of 0.4 \(\lambda\)) and considering the two RT loads: Fig. 18(a) with \(G_{OFF}\) for the OC mode and Fig. 18(b) with \(G_{ON}\) for the SC mode. For a given source direction, compare the difference in gains, \(\Delta G = |G_{ON} - G_{OFF}|\). For instance, for \(\theta_s = 0^\circ\), \(\Delta G = 0.34 \, \text{dB}\) and for \(\theta_s = -30^\circ\), \(\Delta G = 6.77 \, \text{dB}\). Therefore, in this case, since \(\Delta Z_{in} \approx 0 \, \Omega\) for this tags’ arrangement, from (12) and (13) we can deduce that the gain difference \(\Delta G\) is the determining factor of the modulation depth.

In conclusion, the LT’s input impedance and the voltage gain jointly determine the modulation depth. Furthermore, as the distance between the tags increases (whether they are aligned or in some other configuration), the mutual coupling between the two tags decreases and, as a result, the modulation depth is increasingly determined by the source position and thus the gain of the T2T system.

C. BIT ERROR RATE AS METRIC OF OVERALL SYSTEM PERFORMANCE

In order to extend the proposed study and to consider a global T2T system, it is possible to exploit the obtained results in order to determine the BER which is a well-known metric in the field of digital communications [17]. This parameter depends on the modulation depth but also on the type of radio receiver used. The interest of this approach is to offer a way to couple the domains of electromagnetism, antennas, electric circuit, system; and, therefore, to have a methodology allowing to evaluate the global performance of a T2T system. The presented results assume that the demodulator of the LT is based on a passive non-coherent envelope receiver. Further assuming that the collected information signal is degraded by an Additive White Gaussian Noise (AWGN), the BER can be determined as in [16] and can be rewritten as a function of the modulation depth as follows:

\[
BER_{NC} = \frac{1}{2} \cdot \exp \left( -\frac{A_{in} A_{ON} T_s}{8 N_0} \cdot \frac{D^4 - 2D^3 + 2D^2}{2 - D} \right)
\]  

with \(A_{in}\) the RF source’s voltage, \(A_{ON}\) the voltage of the high level “1”, \(T_s\) is the bit time, \(D\) the modulation depth and \(N_0\) is the noise power. It can be directly deduced from this formula that the BER is a strictly decreasing function as the modulation depth increases.

For illustrating, the BER variation has been calculated theoretically by considering that the tags are illuminated by a CW having a power level such that the incident power at the RT’s level is \(-50\, \text{dBm}\). The used values of the input impedance \(Z_{in,ON/OFF}\) and of the gain \(G_{ON/OFF}\) are taken from the simulation results obtained by the EM simulations. The Fig. 19 shows the BER evolution for three separation distances \(d^\prime\left(\frac{\lambda}{10}, \frac{\lambda}{2}, \text{and} \, \lambda\right)\) between the tags, and this, considering the RF source perpendicular to the plane containing the two tags (\(\theta_s = 0^\circ\)). As expected, the best performance in terms of BER is obtained for the distance \(\frac{\lambda}{10}\) between the tags for which the modulation depth is highest in the examples considered here (see Fig. 15), and inversely the worst case is obtained for the distance \(\lambda\) for which the modulation depth is the lowest. Furthermore, Fig. 20 shows the BER when the tags are spaced by a distance \(\frac{\lambda}{4}\) and considering three source orientations (\(\theta_s = 0^\circ, -30^\circ\) and \(-60^\circ\)). As expected from Figure 15 and by a reasoning similar to the previous section (for instance, the higher \(\Delta G\) is the greater the modulation depth, which leads to a lower BER if no major impact is observed on the signal-to-noise ratio), the orientation of the source \(\theta_s = -30^\circ\) leads to better performance. Specifically, the improvement observed here between a source located such that \(\theta_s = -30^\circ\) and a source at \(\theta_s = 0^\circ\), assuming for
VOLUME 10, 2022

18841

depth varies significantly and it is possible to determine
But if the source position is modified, then the modulation
wavelength): with values going from 70% to less than 5%.
between the tags increases from 0.1
shows a decreasing trend by oscillating when the distance
source is symmetrically positioned, the modulation depth
configuration.
very difficult to predict the communication quality for a given
three parameters, which are more or less directly related, it is
source. As the modulation depth is very sensitive to these
geometrical configuration constituted by the two tag antennas
by three main parameters: the switching impedances; the
performance. The modulation depth, which can be considered as an
evaluation metric for the T2T systems, is strongly impacted
the results presented here can provide both limitations and
guidelines to follow. Such applications remain to be developed but
position), a potential misplacement or oversight by the user
which the RF source is fixed (for instance with a known
tags, for example when the person passes through a gate on
security equipment (Fig. 21). Communication between the
tags, which are attached to each piece of safety equipment,
point in clear manner, we propose as a potential application
determination context that is meaningful for the deployment of T2T
antennas could also provide an extra degree of freedom to
differentiate between the two modulation states. Note also
that there are several potential applications of T2T commun-
ications, described for example in the perspective section of [12]. Others are to be imagined in order to find an appli-
cation context that is meaningful for the deployment of T2T
systems.
In this study, to give an example and to illustrate our
point in clear manner, we propose as a potential application a powerless system allowing the monitoring of the use of
security equipment (Fig. 21). Communication between the
tags, which are attached to each piece of safety equipment,
is only established if their relative position is in the correct
configuration. By checking the communication between the
tags, for example when the person passes through a gate on
which the RF source is fixed (for instance with a known
position), a potential misplacement or oversight by the user
can be avoided. Such applications remain to be developed but
the results presented here can provide both limitations and
guidelines to follow.

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