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On the Adequacy of the Far-Field Conditions for Pulsed Radiated EM Fields

Ioan E. Lager, *Senior Member, IEEE*, and A. B. Smolders, *Senior Member, IEEE*

Abstract—The far-field region’s bound is investigated in case of the pulsed electromagnetic field radiation. The value predicted by means of “standard,” time-harmonic considerations is compared with that following from the ratio between the maximum value of the time-domain, near- and far-field magnetic field strength constituents. The adequacy of these criteria is analyzed in the case of a loop-to-loop transfer scenario. The obtained results are of relevance for close-range, wireless digital transfers and provide a safety margin for ensuring the adequacy of the “standard” far-field region’s limit in ultrawideband links.

Index Terms—Near fields, time-domain analysis, ultrawideband (UWB) antennas.

I. INTRODUCTION

THE ULTRAWIDEBAND (UWB) technology is credited among the most propitious avenues for tackling the ever increasing throughput demand in wireless digital communication. As shown in [1], UWB hinges on pulsed electromagnetic (EM) transfer that yields high data-rates [2] and, possibly, ultralow power consumption [3]–[5]. As with any wireless digital transfer, the pulse detection is cornerstone to implementing robust UWB communications. Due to the very low admissible levels of UWB radiated power [6], the accurate knowledge of the *expected* pulse shape at the receiver side is conditional to implementing effective matched filters for discriminating pulses from noise [7, Section III-B] or for developing low-complexity, direct pulse detection circuitry [8]. Note that transmitted pulse signatures undergo significant spatial transformations, their shape only stabilizing in the *far-field region* [9].

While, theoretically, UWB relies on well established *time-domain* (TD) EM field results [1], the design of such systems is far from trivial. Any such design requires the estimation of the received pulse’s shape. This analysis is carried out almost exclusively by means of *time-harmonic* (TH) instruments. Moreover, the radiated EM field is evaluated under the *far-field approximation*, the applicability of which being drawn from the IEEE standard criterion

$$X > 2D^2/\lambda \quad (1)$$

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in which X denotes the distance from the transmitting radiator’s reference center, D its diameter and λ the wavelength at the operational frequency f .¹ This condition is derived based on the phase variation on a (conventional) spherical wavefront [11, Section 14.7]—a typical TH consideration. At variance with this, the TD radiated EM field analysis discriminates between near- and far-field regions based on the field dependence on the distance X and on the corresponding time signatures [13, Sections 26.9 and 26.10].

This letter examines the adequacy of pulsed EM *far-field limits* by comparing the values predicted based on TD and “standard” TH arguments in the case of a loop-to-loop, pulsed EM field transfer scenario. Our study is of relevance for close-range, wireless digital communications as considered in [9], [14]. The discussed experiments will evidence that (1) yields a too low bound of the far-field region and, thus, may result in erroneous prediction of the received pulse’s shape.

II. PULSED RADIATED EM FIELD

A. Prerequisites

The EM field radiated by a small, conducting, current-carrying loop \mathcal{L} is studied. The loop is characterized by its reference center \mathcal{R} , its circumference C , its diameter D , and its oriented area \mathbf{A} ($|\mathbf{A}| = A$), the area’s orientation being associated with that of the electric current in the loop. Position with respect to \mathcal{R} is specified by the position vector \mathbf{X} ($|\mathbf{X}| = X$). For convenience, in the following we shall only consider circular loops. The time coordinate is denoted as t . Normalized spatial and temporal coordinates are marked with a prime. Propagation occurs in free space, with electric permittivity ϵ_0 , magnetic permeability μ_0 and corresponding wavespeed $c_0 = (\epsilon_0\mu_0)^{-1/2}$.

B. Excitation

The loop is excited by the electric current $I(t)$

$$I(t) = I_{\text{peak}} U(t) \quad (2)$$

in which I_{peak} is the peak current and $U(t)$ is a normalized model pulse shape of unit amplitude. *Causal pulse shapes* are considered in this letter, exclusively. Two features deriving from the pulse’s shape are of relevance for our analysis.

- 1) The (conventional) pulse time width t_w , that we take here as the time interval over which the pulse has its fastest temporal variation. This parameter induces a pulse spatial

¹Other criteria, such as $X \gg D$ [11, p. 590] or $X \gg \lambda$ [12, p. 141], are also used for characterizing TH, far-field radiation. Since these criteria do not yield explicit far-field limits, we do not account for them in our study.

extent $c_0 t_w$ that, in turn, yields the admissible upper bound of C (see below).

- 2) The center frequency f_c as following from the pulse's spectral diagram $|\widehat{U}(j\omega)|^2$, with the hat denoting the Fourier transform and $\omega = 2\pi f$ the angular frequency. It is used as a reference for FD metrics.

Two model pulses are employed in this letter: a monopulse type pulse for which generating circuitry is readily available, and a theoretical pulse with a flat spectral diagram. Their t_w and f_c parameters are hereafter discussed.

The time differentiated power exponential pulse (PE_{dt}): It follows from the normalized power exponential (PE) pulse [15] of pulse rise time $t_r > 0$ and pulse rising power $\nu > 1$ (with $\nu \in \mathbb{N}$ throughout this letter) as

$$\begin{aligned} \text{PE}_{\text{dt}}(t) &= t_r N(\nu) \partial_t \text{PE}(t) \\ &= N(\nu) (t'^{\nu-1} - t'^{\nu}) \exp[-\nu(t' - 1)] H(t) \end{aligned} \quad (3)$$

where $t' = t/t_r$, $H(\cdot)$ is the Heaviside unit step function and

$$N(\nu) = \nu^{-1/2} \left(\frac{\nu^{1/2}}{\nu^{1/2} - 1} \right)^{\nu-1} \exp(-\nu^{1/2}) \quad (4)$$

ensures a unit amplitude for PE_{dt}. Its spectral diagram $|\widehat{\text{PE}}_{\text{dt}}(j\omega)|^2$ (see [15]) peaks at the center frequency

$$f_c = \nu^{1/2} / (2\pi t_r) \quad (5)$$

and its pulse width is $t_w = t_r N(\nu)$ (see Appendix). Note that [15] has shown the excellent similarity between PE_{dt} and the pulse generated by the integrated circuit discussed in [16].

The Power Exponential Modulated, Sinc-Cosine Pulse (PE_{s-c}): It was introduced in [17] as a causal pulse with a spectral diagram that approximates a rectangular one over a range $[f_l, f_h]$, $0 < f_l < f_h$, with center frequency $f_c = (f_l + f_h)/2$ and bandwidth $B = f_h - f_l$. Its expression is

$$\begin{aligned} \text{PE}_{\text{s-c}}(t) &= t'^{\nu} \exp[-\nu(t' - 1)] \\ &\times \text{sinc}[B(t - t_r)] \cos[2\pi f_c(t - t_r)] H(t) \end{aligned} \quad (6)$$

with $\text{sinc}(x) \stackrel{\text{def}}{=} \sin(\pi x)/(\pi x)$, for $x \in \mathbb{R}$, t_r being the pulse rise time of the modulating PE pulse, and $\nu > 1$. B and t_r are interrelated via $t_r = K_{\text{sc}}/B$, with $K_{\text{sc}} \in \mathbb{N}$, $K_{\text{sc}} > 2$, while B and f_c are interrelated via $B_{\text{rel}} = B/f_c$, with $B_{\text{rel}} \in [0, 2]$ being the relative bandwidth [17]. The pulse width is taken as

$$t_w = (2f_c)^{-1} = B_{\text{rel}}(2K_{\text{sc}})^{-1} t_r \quad (7)$$

(see Appendix). The pulse's spectral diagram $|\widehat{\text{PE}}_{\text{s-c}}(j\omega)|^2$ was shown in [17] to approximate very well a rectangular shape and is, practically, symmetric about f_c .

C. Radiated Field

The magnetic field strength \mathbf{H} generated by \mathcal{L} is given by [13, p. 761], [9]

$$\mathbf{H}(\mathbf{X}, t) = \mathbf{H}^{\text{NF}}(\mathbf{X}, t) + \mathbf{H}^{\text{IF}}(\mathbf{X}, t) + \mathbf{H}^{\text{FF}}(\mathbf{X}, t) \quad (8)$$

²The rise time t_r of the causal, unipolar PE pulse is defined as the time needed for the pulse to reach its amplitude.

³These ratios were determined in our experiments numerically, by examining the relevant time signatures over suitable time-windows.

with \mathbf{H}^{NF} denoting the *near-field constituent*

$$\mathbf{H}^{\text{NF}}(\mathbf{X}, t) = [3(\boldsymbol{\Xi} \cdot \mathbf{A})\boldsymbol{\Xi} - \mathbf{A}] \frac{I(t - X/c_0)}{4\pi X^3} \quad (9)$$

\mathbf{H}^{IF} the *intermediate-field constituent*

$$\mathbf{H}^{\text{IF}}(\mathbf{X}, t) = [3(\boldsymbol{\Xi} \cdot \mathbf{A})\boldsymbol{\Xi} - \mathbf{A}] \frac{\partial_t I(t - X/c_0)}{4\pi c_0 X^2} \quad (10)$$

and \mathbf{H}^{FF} the *far-field constituent*

$$\mathbf{H}^{\text{FF}}(\mathbf{X}, t) = [(\boldsymbol{\Xi} \cdot \mathbf{A})\boldsymbol{\Xi} - \mathbf{A}] \frac{\partial_t^2 I(t - X/c_0)}{4\pi c_0^2 X}.$$

Here $\boldsymbol{\Xi} = \mathbf{X}/X$ is the unit vector from \mathcal{R} to the observation point. Equations (9)–(11) are derived by assuming that the electric current has negligible spatial variation along \mathcal{L} that, in turn, requires C to be small with respect to the spatial extent of the feeding pulse $c_0 t_w$.

III. FAR-FIELD CONDITIONS FOR RADIATED EM FIELDS

Equations (9)–(11) yield the following metrics for assessing the field behavior in the three EM field radiation regions:

$$R_{\text{N;F}}(X') = \frac{|\mathbf{H}^{\text{NF}}(\mathbf{X}, t)|_{\text{max}}}{|\mathbf{H}^{\text{FF}}(\mathbf{X}, t)|_{\text{max}}} = \frac{|I(t)|_{\text{max}}}{X'^2 t_w^2 |\partial_t^2 I(t)|_{\text{max}}} \quad (12)$$

$$R_{\text{N;I}}(X') = \frac{|\mathbf{H}^{\text{NF}}(\mathbf{X}, t)|_{\text{max}}}{|\mathbf{H}^{\text{IF}}(\mathbf{X}, t)|_{\text{max}}} = \frac{|I(t)|_{\text{max}}}{X' t_w |\partial_t I(t)|_{\text{max}}} \quad (13)$$

in which $X' = X/(c_0 t_w)$. For the considered pulses, the ratios $|I(t)|_{\text{max}}/[t_w |\partial_t^2 I(t)|_{\text{max}}]$ and $|I(t)|_{\text{max}}/[t_w |\partial_t I(t)|_{\text{max}}]$ are functions of the corresponding pulse parameters.³ The EM radiation regions are taken as: *far-field region*, for $X' > X'_{\text{F;t}}$, with $R_{\text{N;F}}(X'_{\text{F;t}}) = \rho_{\text{N;F}}$ and, *intermediate-field region*, for $X' \in (X'_{\text{N;t}}, X'_{\text{F;t}})$, with $R_{\text{N;I}}(X'_{\text{N;t}}) = \rho_{\text{N;I}}$. The parameters $\rho_{\text{N;F}}$ and $\rho_{\text{N;I}}$ must ensure that $\mathbf{H}^{\text{NF}}(\mathbf{X}, t)$ is dominated in the far- and intermediate-field regions by $\mathbf{H}^{\text{FF}}(\mathbf{X}, t)$ and $\mathbf{H}^{\text{IF}}(\mathbf{X}, t)$, respectively, taking $\rho_{\text{N;F}}$ and $\rho_{\text{N;I}}$ as 0.5 being deemed sufficient to this end.

For comparing $X'_{\text{N;t}}$ and $X'_{\text{F;t}}$ with the limit given by (1), the loop's circumference is expressed as $C = K_\lambda \lambda_c$ with K_λ a scaling factor and λ_c the free space wavelength at the center frequency f_c . With this choice, (1) becomes

$$X'_{\text{F;f}}(K_\lambda, \nu) = \frac{4K_\lambda^2}{\pi \sqrt{\nu} N'(\nu)} \quad (14)$$

for a PE_{dt} excitation and

$$X'_{\text{F;f}}(K_\lambda, B_{\text{rel}}, K_{\text{sc}}) = \frac{4K_\lambda^2}{\pi^2} \quad (15)$$

for a PE_{s-c} excitation. Note that, for impedance matching, K_λ should be close to one. However, this choice results in loop circumferences that are not small with respect to $c_0 t_w$. In our experiments we take $K_\lambda = 0.6$, this offering an acceptable compromise between these conflicting conditions.

IV. ILLUSTRATIVE EXPERIMENTS

A first experiment concerns the evaluation of $R_{\text{N;F}}(X')$ and $R_{\text{N;I}}(X')$ for PE_{dt} excitations with varying pulse rising powers ν . The relevant plots are shown in Fig. 1. The $X'_{\text{F;f}}$ values

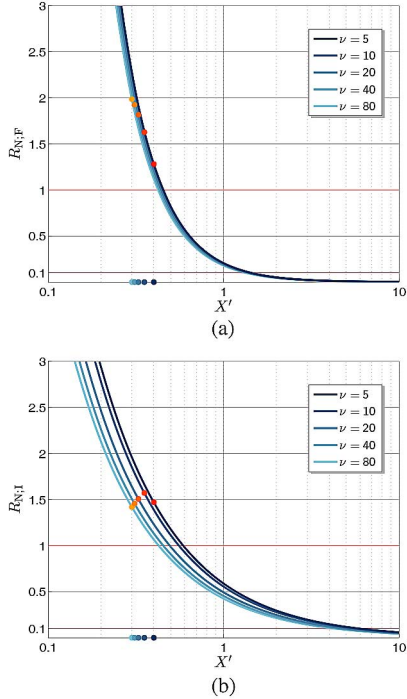


Fig. 1. Constituents ratios dependence on $X' = X/(c_0 t_w)$ for PE_{dt} pulses with various pulse rising powers ν . (a) $R_{N;F}(X')$; (b) $R_{N;I}(X')$. The markers on the ordinates' axis indicate the normalized far-field limit $X'_{F,f}(0.6, \nu)$, their corresponding ratio values being marked by bullets.

TABLE I
 $R_{N;F}(X')$ RATIOS AT $X'_{F,f}(0.6, \nu)$ IN FIG. 1

ν	5	10	20	40	80
$R_{N;F}[X'_{F,f}(0.6, \nu)]$	1.28	1.63	1.82	1.92	1.98

given by (14) are indicated on the ordinates axes and the corresponding ratios are marked on the relevant plots and given in Table I. The plots show that the near-field constituent is dominant at the standardly predicted far-field region's limit. As expected, the ratios drop rapidly and the far-field constituent becomes dominant at $X' \approx 3X'_{F,f}$.

The first experiment concerned a pulse that is intrinsically wideband. Since in practical situations the transmitted signal is band-limited, a second experiment is carried out by using a PE_{s-c} pulse. The $R_{N;F}(X')$ is plotted in Fig. 2 for relative bandwidths of 100%, 10%, and 1%, respectively. The $X'_{F,f}$ values given by (14) are again indicated on the ordinates axes, with the corresponding ratios being marked on the plots and given in Table II. Fig. 2 demonstrates an accentuated increase of $R_{N;F}(X')$ as K_{sc} increases,⁴ while the influence of B_{rel} on the behavior of $R_{N;F}(X')$ is limited. We can now infer that a sharp bandpass filtering may result in large near-field constituents for both narrowband and UWB baseband signals. As with the PE_{dt} feeding, the far-field constituent becomes dominant at $X' \approx 3X'_{F,f}$.

Our study allows concluding that (12) provides a more adequate basis for estimating the far-field region's bound. As for the value predicted by (1), despite the far-field constituent becoming rapidly dominant, the inadequate limit estimate may

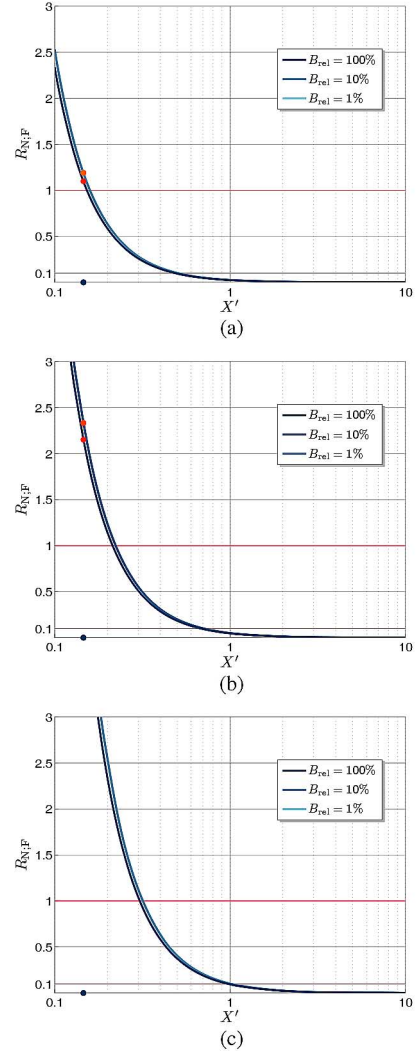


Fig. 2. $R_{N;F}(X')$ dependence on $X' = X/(c_0 t_w)$ for PE_{s-c} pulses with various pulse relative bandwidths B_{rel} and K_{sc} values. (a) $K_{sc} = 5$; (b) $K_{sc} = 7$; (c) $K_{sc} = 10$. The markers on the ordinates' axis indicate the normalized far-field limit $X'_{F,f}(0.6, B_{rel}, K_{sc})$, their corresponding ratio values being marked by bullets.

TABLE II
 $R_{N;F}(X')$ RATIOS AT $X'_{F,f}(0.6, B_{rel}, K_{sc})$ IN FIG. 2

K_{sc}	5	7	10
$R_{N;F}[X'_{F,f}(0.6, 100\%, K_{sc})]$	1.10	2.15	4.39
$R_{N;F}[X'_{F,f}(0.6, 10\%, K_{sc})]$	1.19	2.33	4.76

be detrimental in critical situations, such as those concerning close-range, UWB communications of the type required by, for example, the energetically self-sustainable wireless networks at the core of Internet of Things scenarios [3], [4].

V. CONCLUSION

The pulsed EM field, far-field region's limit was evaluated based on the "standard," time-harmonic condition and the ratio between the maximum value of the near- and far-field magnetic field strength constituents. Illustrative experiments have

⁴In [17], it was shown that the increase in K_{sc} induces an increasingly sharper spectral diagram slope.

shown that the near-field constituent can be the dominant one at the “standard” limit, this categorically influencing the received pulse’s shape. In the case of close-range, ultrafast digital transfers, our study recommends discriminating between the near- and far-field regions based on the near- to far-field constituents’ ratio. Furthermore, we suggest a safety margin of $\times 3$ for ensuring the adequacy of the “standard” far-field region’s limit in the case of pulsed EM field radiation.

The derived results may serve a purpose in the design of the antenna systems for close range, digital communication and in a more adequate estimation of the corresponding received pulses’ shapes.

APPENDIX

DERIVATION OF THE EMPLOYED PULSE WIDTHS

- 1) *The PE_{dt} pulse* In line with [15], the pulse time width t_w is obtained as

$$\begin{aligned} t_w &= \int_0^{t_r} PE_{dt}(t) t = t_r \int_0^{t_r} N(\nu) \partial_t PE(t) t \\ &= t_r N(\nu) PE(t) \Big|_{t=0}^{t_r} = t_r N(\nu) \end{aligned} \quad (16)$$

where use was made of PE_{dt} having unit amplitude and of the relations $PE(0) = 0$ and $PE(t_r) = 1$ (see [15]).

- 2) *The PE_{s-c} pulse*: For determining the applicable pulse time width t_w , (6) is rewritten as

$$\begin{aligned} PE_{s-c}(t) &= t'^{\nu} \exp[-\nu(t' - 1)] \\ &\times \text{sinc}[K_{sc}(t' - 1)] \cos[2\pi K_{sc}/B_{rel}(t' - 1)] H(t). \end{aligned} \quad (17)$$

This relation induces three characteristic pulse widths:

- $t_{w;PE}$, corresponding to the PE. By using [15, Eq. (45)], $t_{w;PE} \in (1.75t_r, 0.33t_r)$ for $\nu < 55$ (this covering all cases of practical relevance).
- $t_{w;sinc}$, corresponding to the sinc part; in view of the definition of the sinc

$$t_{w;sinc} = B^{-1} = K_{sc}^{-1} t_r. \quad (18)$$

It then follows that $t_{w;sinc} < t_{w;PE}$ for $K_{sc} > 3$.

- $t_{w;cos}$ corresponding to the cosine part; it is taken as

$$t_{w;cos} = (2f_c)^{-1} = B_{rel}(2K_{sc})^{-1} t_r. \quad (19)$$

In view of $B_{rel} \leq 2$, it is clear that $t_{w;cos} \leq t_{w;sinc}$.

Since t_w corresponds to the pulse’s fastest temporal variation, we choose $t_w = t_{w;cos}$, (19) being used in the main text.

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