Numerical Simulation of Distributed Devices for the Processing of UltraWideband Information

Sergey L. Chernyshev and Igor B. Vlasov

Abstract A mathematical model of a smooth irregular line with distributed parameters is considered, on which ultra-wideband information is recorded in the form of a change in wave parameters. The numerical solution of the differential equation makes it possible to determine the law of this change. As a result, when an ultra-wideband signal is input to such a line, the reflected signal carries the recorded information.

Keywords Ultrawideband signal · Irregular distributed line · Wave parameters · Reflection coefficient · Numerical solution · Mathematical model

1 Introduction

Ultrawideband (UWB) technologies are gaining increasing application [1–7]. The relative frequency band of ultra-wideband signals exceeds 50% [8]. The IEEE 802.15.4a/b standard provides ultra-wideband wireless communications at speeds up to 500 Mbps [9, 10]. UWB devices are also used when processing signals in radar [11, 12] and when creating antennas [13–15]. In these cases, it is possible to use digital processing if the frequency band occupied by the signal allows the use of an ADC. In the case of a wider frequency band, when such ADCs do not exist, either a stroboscopic signal processing method or UWB irregular distributed lines are used, on which the necessary information is recorded. The characteristics of such lines are formed on the basis of cyber-physical principles, due to distributed parameters [16]. Such lines must be synthesized according to a given frequency dependence of the reflection coefficient [17]. However, one of the main difficulties in creating devices on such lines is the need to solve a differential equation that describes such lines [18]. This equation has the form of Riccati and does not have a general analytical solution.

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In the particular case, after presentation through power series [19], this solution can be found, however, a direct solution to this equation is possible only numerically. This chapter is devoted to this numerical solution and numerical simulation.

2 The Differential Equation of an Irregular Line

Figure 1 shows the dependence of the wave parameters ($\rho(x)$—wave resistance, $\beta(x)$—propagation constant) on the longitudinal coordinate in an irregular distributed line. An electromagnetic wave propagating along this line receives numerous reflections, and as a result, a reflected wave is formed that carries information about the line configuration.

Creating of the necessary configuration allows to record information on the line that the incident ultra-wideband signal will read. When information is entered into the incident signal, its corresponding processing in such a line will occur. However, to record information on an irregular line, it is necessary to develop a method for synthesizing this line, as a result of which the desired dependence is found. Information recording consists in providing the required frequency dependence of the complex reflection coefficient from the input of the line. For such a synthesis, it was required to find the dependence of the internal parameters of the irregular line with this reflection coefficient. The conducted studies consisted in finding a mathematical model of an irregular line in the form of a differential equation. For such a synthesis, it was required to find the dependence of the internal parameters of the irregular line with this reflection coefficient. The conducted studies consisted in finding a mathematical model of an irregular line in the form of a differential equation.

A Riccati-type differential equation describing an irregular non-dissipative transmission line has the form [18]:

$$\frac{\partial \ln(\partial F_{11}(\omega, x)/\partial S_{11}(\omega, x))}{\partial S_{11}(\omega, x)} = 2\left(\frac{1}{S_{11}^*(\omega, x)} - S_{11}(\omega, x)\right)^{-1}, \tag{1}$$

where $S_{11}(\omega, x)$—is the reflection coefficient from the input of the line with a length x, ω—is the circular frequency, $F_{11}(\omega, x)$—is the function depending on the internal

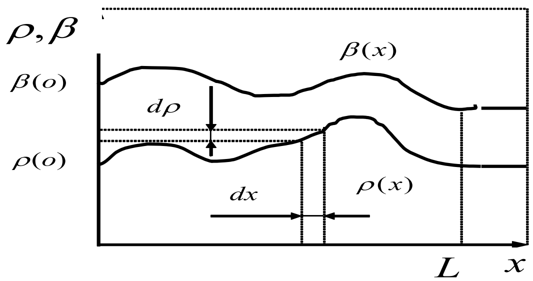


Fig. 1 The dependence of the wave parameters of an irregular line from the longitudinal coordinate

parameters of the line:

$$F_{11}(\omega, x) = \int_0^x N(y)\exp\left[-2j\int_0^y \beta(\omega, z)dz\right]dy,$$

where $N(x) = \frac{1}{2}\frac{d\ln\rho(x)/\rho(0)}{dx}$—the so-called local reflection function.

Equation (1) represents the differential equation at the partial complex variable. In this case, the variable depends on two arguments, of which the argument ω is fixed, and the differentiation of functions is carried out by the argument x. Equation (1) can be converted into the following form, more convenient for synthesis:

$$\frac{\partial^2 F_{11}(\omega, \tau)}{\partial S_{11}^2(\omega, \tau)} = \frac{2S_{11}^*(\omega, \tau)}{1 - |S_{11}((\omega, \tau))|^2}\frac{\partial F_{11}((\omega, \tau))}{\partial S_{11}((\omega, \tau))}. \quad (2)$$

Differentiation of complex functions in this equation is carried out in a new private argument

$$\tau = 2x/V_f(x),$$

where $V_f(x)$—is the phase velocity of the wave propagating in the line. With this definition, the variable represents the delay time of the wave reflected from the cross section of the irregular line with coordinate x.

The general form of the solution of Eq. (2) has the form

$$F_{11}(\omega, \tau) = \int_0^\tau \frac{\partial S_{11}(\omega, t)}{\partial t}\exp\left[\int_0^t \frac{2S_{11}^*(\omega, \upsilon)}{1 - \left|S_{11}^{2)}(\omega, \upsilon)\right|}\frac{\partial S_{11}(\omega, \upsilon)}{\partial \upsilon}d\upsilon\right]dt. \quad (3)$$

This expression implies integration and differentiation with respect to the current coordinate, while the integrands assume knowledge of the line configuration, which is not possible in advance. This fact leads to the need for a numerical solution and the development of an appropriate synthesis algorithm.

3 Description of the Algorithm

The algorithm assumes the following sequence of actions.

1. The search for the necessary line configuration is carried out as a result of synthesis. The criterion of optimality is to provide input line reflection coefficients $S_{11}(\omega_n, \theta)$ given at reference frequencies ω_n with a given accuracy.
2. The solution to Eq. (2) is to find the function $F_{11}(\omega, \tau)|_{\tau=\theta}$, where $\theta = 2L/V_f(L)$—double wave delay at full line length L.

3. This function, as shown in [17, 18], allows one to find the function of local line reflections through the inverse Fourier transform:

4. $N(\tau) = \dfrac{1}{2\pi} \int\limits_{-\infty}^{\infty} F_{11}(\omega, \theta) e^{j\omega\tau} d\omega, \quad \tau = [0; \theta].$ (4)

5. The necessary law for changing the wave resistance of an irregular line that implements a given frequency dependence of the complex reflection coefficient $S_{11}(\omega, \theta)$ is determined as follows:

6. $\rho(\tau) = \rho(0) e^{2\int_0^\tau N(t)dt}.$

Thus, the described algorithm for synthesizing an irregular line from a given frequency dependence of the complex reflection coefficient includes a solution to Eq. (2), which does not have an analytical solution and requires a numerical solution.

In the numerical solution, we use the Newton-Raphson method. When iterating closer to the solution, the function $F_{11}(S_{11})$ will take values $F_{11(K)}(S_{11})$, where k is the iteration number $k = 1, 2, \ldots$.. By expanding the function $F_{11(K)}(S_{11})$ in a series around the point $F_{11(K-1)}(S_{11}) F_{11(K-1)}(S_{11})$ and restricting ourselves to a second-order term, we obtain

$$F_{11(k)}(S_{11}) = F_{11(k-1)}(S_{11}) + \left.\frac{\partial F_{11}}{\partial S_{11}}\right|_{k-1} \big(S_{11}(\omega_n, \theta) - S_{11(k-1)}\big) + \frac{1}{2} \left.\frac{\partial^2 F_{11}}{\partial S_{11}^2}\right|_{k-1} \big(S_{11}(\omega_n, \theta) - S_{11(k-1)}\big)^2.$$

If we express the second derivative from Eq. (2), we obtain

$$F_{11(k)}(S_{11}) = F_{11(k-1)}(S_{11}) + \left.\frac{\partial F_{11}}{\partial S_{11}}\right|_{k-1} \big(S_{11}(\omega_n, \theta) - S_{11(k-1)}\big) \left[1 + \frac{S^*_{11(k-1)}}{1 - \left|S^2_{11(k-1)}\right|} \big(S_{11}(\omega_n, \theta) - S_{11(k-1)}\big)\right], \quad (5)$$

where $S_{11}(\omega_n, \theta)$ is the specified value of the coefficient of reflection from the line at the reference frequency $\omega_n \quad n = 1, 2, \ldots M$.

Iterative procedures (5) are carried out at each of the reference frequencies ω_n.

For such a solution, it is necessary to set some dependence as the initial dependence $N_0(\tau)$. We find this initial approximation based on the equality found in [19] $F_{11}(\omega, \theta) = e^{j\varphi_{11}(\omega,\theta)} \mathrm{Arth}|S_{11}(\omega, \theta)|$, where $\varphi_{11}(\omega, \theta) = \arg S_{11}(\omega, \theta)$, and applying Eq. (2). For this line configuration, using chain theory methods we find $S_{11(0)}(\omega, \tau)$—the reflection coefficient from the line of initial.

Note that the derivative in (5) can be found from expression (3) by differentiating its left and right parts:

$$\left.\frac{\partial F_{11}(\omega_n, \tau)}{\partial S_{11}(\omega_n, \tau)}\right|_{k-1} = \exp\left[\int\limits_0^{\tau} \frac{2S^*_{11(k-1)}(\omega, t)}{1 - \left|S_{11(k-1)}(\omega, t)\right|^2} \frac{\partial S_{11(k-1)}(\omega, t)}{\partial t} dt\right].$$

The integral in this equation is calculated numerically, since the dependence $S_{11(k-1)}(\omega_n, \tau)$, which is the complex reflection coefficient of the line with the length τ at the $(k-1)$-th iteration, is determined for the dependence $N_{k-1}(\tau)$ that was found earlier at the same iteration.

The numerical solution occurs relatively quickly, at 3–4 iterations, which is explained by the choice of a good initial approximation, which is so necessary for the Newton-Raphson method, which is one of the fastest among nonlinear optimization methods.

The optimality criterion for this algorithm is to minimize the residuals and fall into the acceptability region $\sum_{n=1}^{N} \left|S_{11(k)}(\omega_n, \theta) - S_{11}(\omega_n, \theta)\right|^2 < \varepsilon$, where $\varepsilon =$ is the given accuracy.

Figure 2 shows a simplified block diagram of the described algorithm.

After finding the function $F_{11}(\omega, \tau)|_{\tau=\theta}$, we find the local reflection function $N(\tau)$ using transformation (4). Knowing $N(\tau)$, we find the law of change in the wave resistance of an irregular distributed line, which allows you to implement the information recorded on the line.

As an example, Fig. 3 shows the dependence of the width of a microstrip irregular distributed line on a substrate 1 mm high with a dielectric constant of 9.8, synthesized from a given frequency dependence, the amplitude-frequency and phase-frequency characteristics of which are shown in Fig. 4a, b.

4 Conclusion

The distributed nature of irregular lines implementing the cyberphysical principles of processing ultra-wideband information required the solution of a non-linear Riccati-type equation and the implementation of an algorithm for its numerical solution. Such a numerical model made it possible to synthesize irregular lines in order to record the necessary ultra-wideband information.

The information that must be recorded on an irregular line is the aforementioned frequency dependence of the complex reflection coefficient $S_{11}(\omega, \theta)$, which provides the conversion of the signal incident on the line.

So, if the spectrum of the incident ultra-wideband signal is equal $a(\omega)$, then the reflected signal will have a spectrum $b(\omega) = S_{11}(\omega)a(\omega)$, and in the time domain the signal $b(t) = \int_0^t g_{11}(\tau)a(t-\tau)d\tau$ will be reflected, where $g_{11}(t)$ is the impulse response of the reflection line. The synthesis of such irregular lines based on the

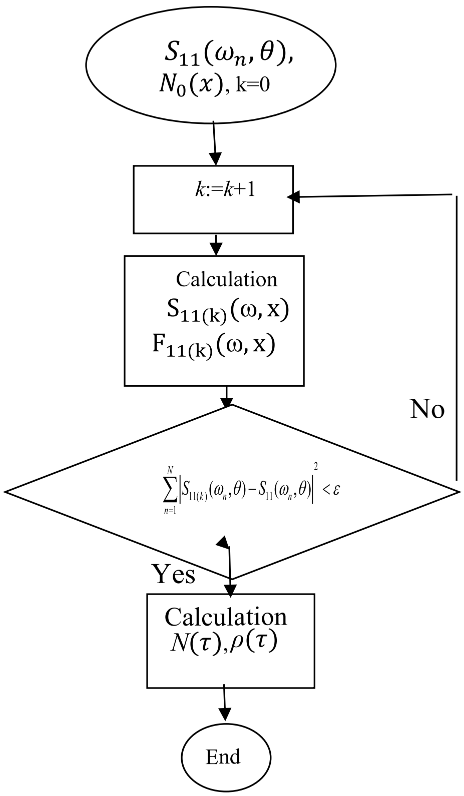


Fig. 2 The simplified scheme of the algorithm

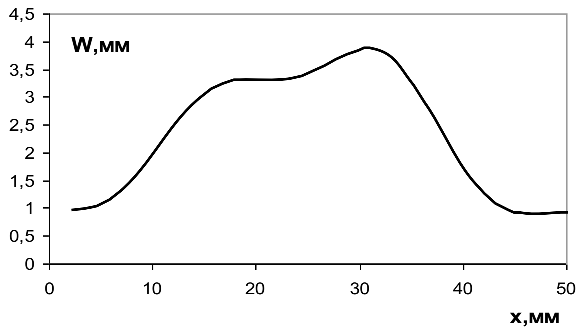
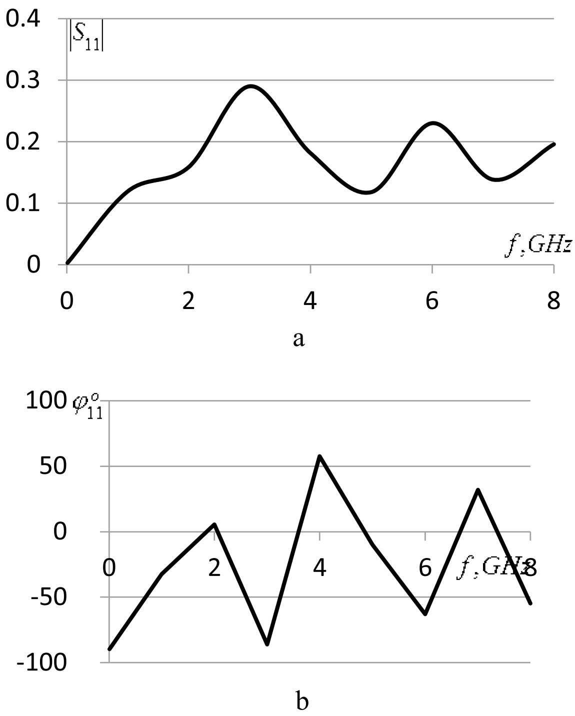


Fig. 3 The dependence of the width of the synthesized microstrip line

numerical solution of differential Eq. (2) allows the processing of information of ultra-wideband signals.

Fig. 4 Frequency dependences: **a** amplitude-frequency, **b** phase-frequency



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