very important to include in system descriptions the angular behavior of the antennas since all transmitted or received paths, e.g., in indoor applications, are weighted by the antenna patterns and therefore contribute with different time domain characteristics, e.g., polarization, amplitude, phase, and delay to the received voltage $u_{\mathrm{Rx}}(t)$. In Fig. 3, the time-domain link level scheme is shown. The small graphs symbolize the typical influence of the link contributions. The initial pulse and its derivative are sketched.

Any antenna differentiates any signal, because antennas do not radiate dc signals. Equations (1) and (2) have, after conversion to the time domain, the form presented in (3) and (4), respectively. Fundamental operations like the multiplication in the frequency domain are substituted by convolution in the time domain. Equation (3) relates the radiated field strength $\mathbf{e}_{\mathrm{Tx}}(t,\mathbf{r})$ to the excitation voltage $u_{\mathrm{Tx}}(t)$ and the transient response of the transmit antenna $\mathbf{h}_{\mathrm{Tx}}(t,\theta_{\mathrm{Tx}},\psi_{\mathrm{Tx}})$ [5]. In (4), again only free-space propagation is regarded (line of sight Tx-Rx)

$$\frac{\mathbf{e}_{Tx}(t,\mathbf{r})}{\sqrt{Z_0}} = \frac{1}{2\pi r_{TxRx}c_0}\delta\left(t-\frac{r_{TxRx}}{c_0}\right) * \mathbf{h}_{Tx}(t,\theta_{Tx},\psi_{Tx}) * \frac{\partial}{\partial t}\frac{u_{Tx}(t)}{\sqrt{Z_{C,Tx}}} \tag{3}$$

$$\frac{u_{Rx}(t)}{\sqrt{Z_{C,Rx}}} = \mathbf{h}^{T}_{Rx}(t,\theta_{Rx},\psi_{Rx}) * \frac{1}{2\pi r_{TxRx}c_0}\delta\left(t-\frac{r_{TxRx}}{c_0}\right) * \mathbf{h}_{Tx}(t,\theta_{Tx},\psi_{Tx}) * \frac{\partial}{\partial t}\frac{u_{Tx}(t)}{\sqrt{Z_{C,Tx}}}. \tag{4}$$

The delay time of the channel is taken care of by the antenna spacing r_{TxRx}. The transient response functions are also reciprocal, $\mathbf{h}_{\mathrm{Tx}} = \mathbf{h}_{\mathrm{Rx}}$, but the direction of signal flow with respect to the coordinate system has to be taken into account.

The antennas are an essential part of any wireless system, and their properties have to be carefully taken into account during all steps of the system design. For UWB impulse systems, this is vital.

II. UWB DEFINITIONS AND ANTENNA PARAMETERS

The desired operating frequencies are given by:

- U.S. FCC regulation [6] as 3.1 to 10.6 GHz;
- European regulation [7] (2007|131|EC) as 6.0 to 8.5 GHz;
- special allocations, e.g., ground penetrating radar or wall radar;

but not limited to these. A general definition of UWB is stated with the relative bandwidth

$$2(f_H - f_L)/(f_H + f_L) > 0.2 \tag{5}$$

where f_{H} and f_{L} are the upper and lower band limits, respectively. Relative bandwidths in excess of 100% are possible for some antenna types.

A. Antenna Characterization Parameters

In contrast to classic narrow-band antenna theory, where the antenna characteristics are regarded for only a small bandwidth, the characterization of antennas over an ultrawide frequency range requires new specific quantities and representations [1], [8]. In this section, both time-domain and frequency-domain representations are regarded. Depending on the application, the relevant ones have to be selected. In general, the Fourier transforms forward and backward are the operations to switch from frequency domain to time domain, and vice versa.

An impulse fed to an UWB antenna is subject to:

- differentiation;
- dispersion (energy storage);
- radiation;
- losses (dielectric/ohmic).

The antenna's complete behavior, including frequency dependency, can be described by the linear system theory. The characteristics are expressed either by a time-domain impulse response $\mathbf{h}(t,\theta_{\mathrm{Tx}},\psi_{\mathrm{Tx}})$ or by the frequency-domain transfer function $\mathbf{H}(f,\theta_{\mathrm{Tx}},\psi_{\mathrm{Tx}})$, as given earlier, both of which contain the full information on the antenna radiation. The dispersion of the antenna can be analyzed by regarding the analytic impulse response, which is

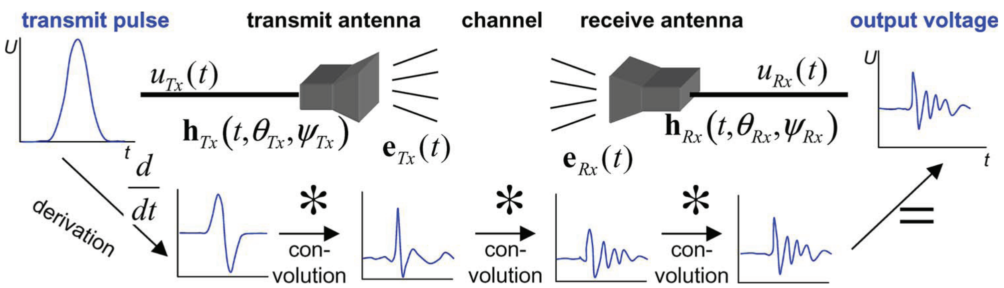

Fig. 3. *UWB system link level characterization in time domain.*