1 Introduction

Jens Timmermann and Thomas Zwick

This book concentrates on UWB RF systems. In the analog RF frontend, a high relative bandwidth and not necessarily a high absolute bandwidth poses new challenges to the RF system design. We are therefore concentrating on the lower frequency range of around 1–10 GHz where a large variety of system concepts are under investigation worldwide. A short list of typical applications envisioned by researchers and companies is:

- high data rate, short range applications: typically portable devices and built into antenna systems in consumer electronics or into access point infrastructure
- low data rate, wider range, eventually combined with a ranging application: small portable devices (also wearable systems etc.) combined with integrated antenna system for the accesspoint infrastructure
- low data rate and a high number of users (sensor networks), typically small integrated antennas
- medical imaging for diagnostics, radar systems in combination with antenna arrays
- localization for industrial, medical and commercial applications
- high resolution radar for various applications (e.g. mine detection, through-wall imaging, material inspection).

This chapter provides the definition of UWB signals and regulatory aspects.

1.1 Definition of UWB signals

An ultra-wideband signal is either a signal with a simultaneous bandwidth B that satisfies the condition

$$B \geq 500 \text{ MHz} \tag{1.1}$$

or it is a signal with a relative (=fractional) bandwidth f_r larger than 20% [46]. The relative bandwidth is defined as

$$B_\mathrm{r} = \frac{f_\mathrm{u} - f_\mathrm{l}}{f_\mathrm{c}}. \tag{1.2}$$

Table 1.1 US FCC regulations: limits of the PSD for indoor applications [46].

Frequency range GHz	PSD dBm/MHz
Below 0.96	−41.3
0.96–1.61	−75.3
1.61–1.99	−53.3
1.99–3.1	−51.3
3.1–10.6	−41.3
>10.6	−51.3

In this equation f_u and f_l denote the upper and lower frequencies at which the power spectral density is 10 dB below its maximum. f_c is the center frequency:

$$f_\mathrm{c} = \frac{f_\mathrm{u} + f_\mathrm{l}}{2}. \tag{1.3}$$

1.2 Worldwide regulations

The maximum emission levels of UWB devices are defined by specific UWB regulations. Different countries have released regulations (e.g. the National Frequency Plan) which cover the following points:

- applications of UWB technology (indoor, outdoor, portable, fixed installed)
- allocated frequency ranges
- maximum emission levels: power spectral density (PSD) in terms of equivalent isotropically radiated power (EIRP)
- techniques to mitigate (reduce) possible interference caused by the UWB device.

UWB regulations have been released by the United States, Europe, Japan, Korea, Singapore and China. The US Federal Communications Commission (FCC) was the first authority worldwide that released UWB regulations in February 2002 [46]. According to the FCC regulations, the usable frequency range for UWB indoor applications is between 3.1 and 10.6 GHz. The emission limits are defined in Table 1.1.

In Europe, the regulations have been available since March 2006 [44]. They describe respective levels for indoor applications. The (technically) usable frequency range in the EU is allocated to two bands: 4.2–4.8 and 6–8.5 GHz. However there are some constraints on the first band – a mitigation technique has to be used. Without mitigation, the requirement is −70 dBm/MHz rather than −41.3 dBm/MHz. The maximum emission levels resulting from the European regulations are summarized in Table 1.2.

For completeness, Table 1.3 lists the technically usable frequency ranges for all the countries that have released UWB regulations. The maximum emission level is −41.3 dBm/MHz in all cases. UWB signals present an ultra-large bandwidth, which can, for example, be used to realize very high data rates (> 100 Mbit/s). It is also possible to

Table 1.2 ECC regulation: limits of the PSD for indoor applications [44].

Frequency range GHz	PSD dBm/MHz
Below 1.6	−90.0
1.6–2.7	−85.0
2.7–3.4	−70.0
3.4–3.8	−80.0
3.8–4.2	−70.0
4.2–4.8	−70.0/−41.3
4.8–6.0	−70
6.0–8.5	−41.3
8.5–10.6	−65
>10.6	−85

Table 1.3 Technically usable frequency range for countries with UWB regulation [16, 34, 41].

Nation	1st frequency range GHz	2nd frequency range GHz
USA	3.1–10.6	–
Europa	4.2–4.8	6.0–8.5
Japan	3.4–4.8	7.25–10.25
Korea	3.1–4.8	7.2–10.2
Singapore	4.2–4.8	6.0–9.0
China	4.2–4.8	6.0–9.0

make use of the ultra-fine time resolution (with applications in localization and imaging). However, one has to consider that the total emitted power has to be very low to fulfill the regulatory aspects: the limitation to −41.3 dBm/MHz between 3.1 and 10.6 GHz results in a total transmitted power of only 0.56 mW for the FCC mask. For the European mask, the value is even smaller. As a consequence, commercial UWB transmission is limited to short range applications. To exploit the technically usable UWB frequency range, two different approaches are possible:

- Approach 1: Transmission based on ultra-short pulses, which cover an ultra-wide bandwidth (also called impulse radio).
- Approach 2: Transmission based on Orthogonal Frequency Division Multiplexing (OFDM), where the total UWB bandwidth is subdivided into (and exploited by) a set of broadband OFDM channels.

Considering Approach 1, it is desirable to make use of pulses that show a nearly constant spectrum in the technically usable frequency range in order to maximize the overall signal power with regard to the emission regulation. On the other hand, a cost-efficient solution may be to use classical pulse shapes that are easy to generate, but not very efficient with respect to the exploitation of the mask (hence degraded signal-to-noise ratio and degraded performance). A pulse shape that is easy to generate is the Gaussian monocycle or one of its derivatives. In general, impulse radio transmission does not make use of a carrier, which means that the signal is directly radiated via the UWB antenna. Impulse radio therefore has the potential of realization with reduced complexity in comparison with traditional narrowband transceivers.

For Approach 2, the spectral mask can be exploited more efficiently. On the other hand, OFDM transmission leads to increased complexity in terms of signal processing. The overall power consumption due to the increased signal processing may be higher compared to impulse radio transmission. The selection between the two approaches depends on the application and will be a case by case decision.

Cambridge University Press & Assessment
978-1-107-01555-5 — Ultra-wideband RF System Engineering
Edited by Thomas Zwick , Werner Wiesbeck , Jens Timmermann , Grzegorz Adamiuk
Excerpt
More Information

2 Fundamentals of UWB radio transmission

Jens Timmermann and Thomas Zwick

UWB is an umbrella term that mainly indicates that a very large absolute bandwidth ($B_a > 500$ MHz) or a very large relative bandwidth ($B_r = 2[f_u - f_l]/[f_u + f_l] > 0.2$) in the RF spectrum is used instantaneously by the system. With this definition, no special purpose or application and no special modulation is defined but it implies that the components of the system must be capable of handling this wide spectrum. As already mentioned in the previous chapter for RF frontends, on the whole it is the relative bandwidth that poses new challenges, so system aspects for a very large relative bandwidth are mainly discussed here. This chapter provides a mathematical description of the UWB radio channel including the antennas and measures to characterize the UWB performance of the analog frontend, including the radio channel in the frequency domain (FD) and in the time domain (TD). The chapter presents two methods to exploit an ultra-wide bandwidth: the transmission of short pulses in the baseband (impulse radio transmission), and the transmission by a multi-carrier technique called orthogonal frequency division multiplexing (OFDM). For impulse radio, the most common pulse shapes are introduced together with methods to generate them. Finally, modulation and coding techniques are considered as well as basic transmitter and receiver architectures. The coordinate system is given in Fig. 2.1.

2.1 Description of the UWB radio channel

Typically, narrow-band systems are described in the frequency domain. The characteristic parameters are then assumed to be constant over the considered bandwidth. Due to the large relative bandwidth to be considered for UWB systems, the frequency-dependent characteristics of the antennas and the frequency-dependent behavior of the channel must be taken into account. On the other hand, UWB systems are often realized in an impulse-based technology, so a time domain description might be advantageous as well [154]. Hence there is a requirement for both a frequency domain representation and a time domain representation of the system description.

2.1.1 Time domain and frequency domain

Ultra-wideband signals can be represented both in the TD and in the FD. In the TD, the signal is described as a function of time. The Fourier transformation of a signal in

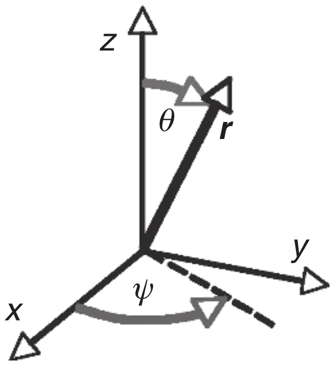

Figure 2.1 Coordinate system for UWB link and antenna characterization.

the TD leads to a representation in the FD, called the spectrum. The inverse Fourier transformation of the spectrum leads to the representation in the TD. Mathematically speaking, this means: to perform a (continuous) Fourier transformation, the continuous complex signal $f(t)$ ($\Re \mapsto C; t \mapsto f(t)$) in the TD has to fulfill the following condition:

$$\int |f(t)| dt < \infty. \tag{2.1}$$

This condition means that the signal is integrable, which is normally the case for technical signals. The Fourier transformation is defined as:

$$\mathcal{F}(f(t)) = F(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t} dt \tag{2.2}$$

with $\omega = 2\pi f$, where f is the frequency. The inverse Fourier transformation is defined as:

$$\mathcal{F}^{-1}(F(\omega)) = f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \cdot e^{j\omega t} dt. \tag{2.3}$$

The power spectral density (PSD) of a signal can be obtained by the absolute value of the squared spectrum. The unit of the PSD is W/Hz. For UWB applications, dBm/MHz is often used where 0 dBm equals 1 mW. The representation in terms of PSD is used, for example, to check if the signal fits into the allocated frequency mask.

There are measures to describe the signal in the TD or in the FD. One example in the FD is the so-called group delay versus frequency, which is

$$\tau_g = -\frac{1}{2\pi} \cdot \frac{d\varphi(f)}{df}, \tag{2.4}$$

where $\varphi(f)$ is the phase of the spectrum and f is the frequency of the signal. A constant group delay means linear phase behavior, which is often required. Examples of measures of a signal in the TD are the pulse width and the pulse repetition time.

Besides UWB signals, UWB components (such as antennas, filters) and the UWB propagation channel can be described in the TD and the FD respectively. In the FD, the behavior is characterized by a complex transfer function (amplitude and phase information). An inverse Fourier transformation of the FD signal leads to the impulse response in the TD. For example, a function that is constant versus $f \in \Re$ in the FD (= flat spectrum) corresponds to an impulse at $t = 0$ in the TD. Band limitation in the FD by any system component can cause spreading of the impulse and lead to signal degradation. Detailed definitions on the measures in the TD and FD are provided in Section 2.3. Further information can also be found in books on UWB fundamentals [120, 141].

In the beginning many new and exciting topics arose from the exploration of UWB time domain short pulse modulation schemes that complemented the known frequency domain sinusoidal carrier-based systems. However the range of modulation solutions is wider and the wideband frequency domain modulation schemes showed their advantages. In between time domain and frequency domain, solutions like direct sequence spread spectrum modulation schemes and wideband carrier-based OFDM signals also exist, which look like passband pulses in the time domain. Depending on the modulation scheme and application, the RF components must be characterized in the TD, FD, or even both. To check if a signal is compliant with the allocated spectral mask, a representation in the FD is always necessary.

2.1.2 UWB channel in the frequency domain

For the FD description it is assumed that the transmit antenna is excited with a continuous wave signal with frequency f. The relevant parameters for the FD link description are:

- amplitude of transmit signal $U_{\mathrm{Tx}}(f)$ (V)
- amplitude of receive signal $U_{\mathrm{Rx}}(f)$ (V)
- radiated field strength $\mathbf{E}_{\mathrm{Tx}}(f, r, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}})$ (V/m) at distance r from antenna
- transfer function of the transmit antenna $\mathbf{H}_{\mathrm{Tx}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}})$ (m)
- transfer function of the receive antenna $\mathbf{H}_{\mathrm{Rx}}(f, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}})$ (m)
- characteristic transmit antenna impedance $Z_{\mathrm{C,Tx}}(f)$ (Ω)
- characteristic receive antenna impedance $Z_{\mathrm{C,Rx}}(f)$ (Ω)
- antenna gain $G(f, \theta, \psi)$
- distance between Tx–Rx antennas r_{TxRx} (m).

The antenna transfer function is a two-dimensional vector with two orthogonal polarization components. The unit of the transfer function is meter and it is equivalent to an effective antenna height, depending on frequency [157]. The characteristic antenna impedance defines the air interface reflection coefficient. $\mathbf{H}_{\mathrm{Tx}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}})$ is the transfer function of the transmit antenna that relates the transmit signal $U_{\mathrm{Tx}}(f)$ to the radiated field strength $\mathbf{E}_{\mathrm{Tx}}(f, r)$ at a distance r for an antenna in the transmit mode:

$$\frac{\mathbf{E}_{\mathrm{Tx}}(f, r)}{\sqrt{Z_0}} = \frac{e^{-j\omega r/c_0}}{2\pi r c_0} \mathbf{H}_{\mathrm{Tx}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}}) \cdot j\omega \frac{U_{\mathrm{Tx}}(f)}{\sqrt{Z_{\mathrm{C,Tx}}}} . \tag{2.5}$$

With the transfer function of the receive antenna $\mathbf{H}_{\mathrm{Tx}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}})$ the received signal amplitude $U_{\mathrm{Rx}}(f)$ can be related to the incident field $\mathbf{E}_{\mathrm{Rx}}(f, \mathbf{r})$ (in the frequency domain)

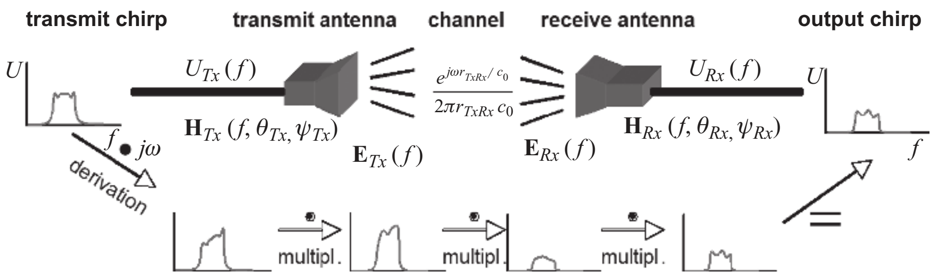

Figure 2.2 Frequency domain system link level characterization for free space. ©2009 IEEE; reprinted with permission from [179].

at an antenna in the receive mode:

$$\frac{U_{\mathrm{Rx}}(f)}{\sqrt{Z_{\mathrm{C,Rx}}}} = \mathbf{H}_{\mathrm{Rx}}^{T}(f, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}}) \cdot \frac{\mathbf{E}_{\mathrm{Tx}}(f, r_{\mathrm{TxRx}})}{\sqrt{Z_0}}, \tag{2.6}$$

with $\mathbf{H}_{\mathrm{Rx}}^{T}$ being the transpose of $\mathbf{H}_{\mathrm{Rx}}$. The total analytical description of a LOS free-space UWB propagation link is given by:

$$\frac{U_{\mathrm{Rx}}(f)}{\sqrt{Z_{\mathrm{C,Rx}}}} = \mathbf{H}_{\mathrm{Rx}}^{T}(f, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}}) \cdot \frac{e^{-j\omega r_{\mathrm{TxRx}}/c_0}}{2\pi r_{\mathrm{TxRx}} c_0} \cdot \mathbf{H}_{\mathrm{Tx}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}}) \cdot j\omega \frac{U_{\mathrm{Tx}}(f)}{\sqrt{Z_{\mathrm{C,Tx}}}}. \tag{2.7}$$

With these parameters, the Tx–Rx free-space UWB link is illustrated in Fig. 2.2. In the frequency domain description the consecutive subsystem parameters are multiplied. The small graphs symbolize the typical influence of the link contributions. The initial chirp and its derivatives are sketched. Since antennas are reciprocal, so are their transfer functions. Therefore the transfer function of an antenna $\mathbf{H}_{\mathrm{ant}}$ can be used at both ends of the channel; however, the direction of the signal flow with respect to the coordinate system has to be taken into account (see transposed $\mathbf{H}_{\mathrm{Rx}}$ in (2.6)). Two orthogonal polarizations are included in the Tx and Rx transfer functions, as noted above. While in narrow band systems the radiation angles θ and ψ influence only the polarization, amplitude and the phase of the signal, in UWB systems they also influence the entire frequency-dependent signal characteristics.

For UWB links in rich scattering environments (e.g. indoors), the influence of the multipath propagation must be added to (2.7). The multipath radio propagation channel can be described by a frequency-dependent full polarimetric channel transfer matrix $\mathbf{H}_{\mathrm{PC}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}}, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}})$. The total analytical description of a multipath UWB propagation link can then be given by

$$\begin{aligned}\frac{U_{\mathrm{Rx}}(f)}{\sqrt{Z_{\mathrm{C,Rx}}}} = \int_{\theta_{\mathrm{Tx}}=0}^{\pi} \int_{\psi_{\mathrm{Tx}}=0}^{2\pi} \int_{\theta_{\mathrm{Rx}}=0}^{\pi} \int_{\psi_{\mathrm{Rx}}=0}^{2\pi} \Bigg[& \mathbf{H}_{\mathrm{Rx}}^{T}(f, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}}) \\ & \cdot \mathbf{H}_{\mathrm{PC}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}}, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}}) \cdot \mathbf{H}_{\mathrm{Tx}}(f, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}}) \Bigg] \cdot j\omega \frac{U_{\mathrm{Tx}}(f)}{\sqrt{Z_{\mathrm{C,Tx}}}}.\end{aligned} \tag{2.8}$$

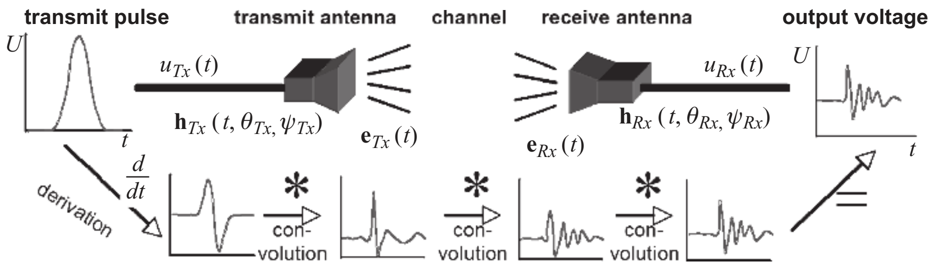

Figure 2.3 UWB system link level characterization in the time domain for free space. ©2009 IEEE; reprinted with permission from [179].

2.1.3 UWB channel in the time domain

For the time domain description it is assumed that the transmit antenna is excited with a Dirac pulse. The elements of the UWB time domain link characterization are:

- amplitude of transmit signal $u_{\mathrm{Tx}}(t)$ (V)
- amplitude of receive signal $u_{\mathrm{Rx}}(t)$ (V)
- impulse response of the transmit antenna $\mathbf{h}_{\mathrm{Tx}}(t, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}})$ (m/s)
- impulse response of the receive antenna $\mathbf{h}_{\mathrm{Rx}}(t, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}})$ (m/s)
- radiated field strength $\mathbf{e}(t, r, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}})$ (V/m) at position r
- distance between Tx–Rx antennas r_{TxRx} (m).

The antenna's transient impulse response is dependent on time, and also on the angles of departure θ_{Tx}, ψ_{Tx}, the respective angles of arrival θ_{Rx}, ψ_{Rx}, and the polarization [159]. As a consequence the antennas do not radiate the same pulse in all directions, which may cause severe problems in UWB communications and radar. For example, in the case of a multipath environment it is very important to include the angular behavior of the antennas in the system description since all transmitted or received paths are weighted by the antenna's characteristics, 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. 2.3 the free-space 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.

Since antennas do not radiate DC signals, any antenna will differentiate the radiated signal. Analog to (2.5) and (2.7), the LOS free-space time domain link can be given by:

$$\frac{\mathbf{e}_{\mathrm{Tx}}(t, \mathbf{r})}{\sqrt{Z_0}} = \frac{\delta(t - \frac{r}{c_0})}{2\pi r_{\mathrm{TxRx}} c_0} * \mathbf{h}_{\mathrm{Tx}}(t, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}}) * \frac{\partial}{\partial t} \frac{u_{\mathrm{Tx}}(t)}{\sqrt{Z_{\mathrm{C,Tx}}}}, \tag{2.9}$$

$$\frac{u_{Rx}(t)}{\sqrt{Z_{\mathrm{C,Rx}}}} = \mathbf{h}^T_{\mathrm{Rx}}(t, \theta_{\mathrm{Rx}}, \psi_{\mathrm{Rx}}) * \frac{\delta(t - \frac{r_{\mathrm{TxRx}}}{c_0})}{2\pi r_{\mathrm{TxRx}} c_0} * \mathbf{h}_{\mathrm{Tx}}(t, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}}) * \frac{\partial}{\partial t} \frac{u_{\mathrm{Tx}}(t)}{\sqrt{Z_{\mathrm{C,Tx}}}}. \tag{2.10}$$

The fundamental multiplication operation in the FD corresponds to a convolution in the TD. Equation (2.9) relates the radiated field strength $\mathbf{e}_{\mathrm{Tx}}(t, r)$ at the distance r to the excitation voltage $u_{\mathrm{Tx}}(t)$ and the transient response of the transmit antenna $\mathbf{h}_{\mathrm{Tx}}(t, \theta_{\mathrm{Tx}}, \psi_{\mathrm{Tx}})$

[45]. In (2.10) again only free space LOS propagation is regarded (line of sight between Tx and Rx). Also the antenna's transient response function h_{ant} is reciprocal, so it can be applied at either Tx or Rx, but again 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 considered carefully during all steps of the system design. For UWB impulse systems this is vital. For rich scattering environments (2.10) can be extended analog to (2.8).

2.2 UWB propagation channel modeling

To calculate exactly the wave propagation between two antennas in a given scenario, one would have to solve the Maxwell equations numerically. An investigation using a finite difference time domain solution can be found in [163]. Due to the large ratio between scenario size and wavelength this is extremely time- and memory-consuming, or even impossible for nearly all interesting scenarios. Therefore an approximation is usually used for propagation channel modeling: geometrical optics [23], where each propagation path between transmitter and receiver with all its reflections, diffractions, transmissions and scattering processes is modeled by a multipath component, usually called a "ray". With N being the number of discrete multipath components, (2.8) changes to

$$\frac{U_{\text{Rx}}(f)}{\sqrt{Z_{\text{C,Rx}}}} = \sum_{n=1}^{N} \mathbf{H}_{\text{Rx}}^{T}(f, \theta_{\text{Rx},n}, \psi_{\text{Rx},n}) \cdot \mathbf{H}_{\text{PC,n}}(f) e^{j\omega r_{\text{TxRx},n}/c_0} \cdot \mathbf{H}_{\text{Tx}}(f, \theta_{\text{Tx},n}, \psi_{\text{Tx},n}) \cdot j\omega \frac{U_{\text{Tx}}(f)}{\sqrt{Z_{\text{C,Tx}}}} \tag{2.11}$$

with

- number of multipath components N and multipath component index n
- total path length of multipath components $r_{\text{TxRx},n}$
- transmit direction of multipath component given by $\theta_{\text{Tx},n}$ and $\psi_{\text{Tx},n}$
- receive direction of multipath component given by $\theta_{\text{Rx},n}$ and $\psi_{\text{Rx},n}$
- frequency-dependent full polarimetric channel transfer matrix of nth multipath component $\mathbf{H}_{\text{PC,n}}(f)$.

In scenarios with no other relevant multipath component other than just a line-of-sight (LOS) path, the attenuation of a signal can be determined by the free-space attenuation of the single LOS path only (see (2.7)). Assuming isotropic antennas, the free-space attenuation $L_{\text{FS}}(f)$ at a frequency f can be described by the Friis equation

$$L_{\text{FS}}(f) = \left(\frac{\lambda}{4\pi r_{\text{TxRx}}}\right)^2 \sim \frac{1}{f^2} \tag{2.12}$$

where r_{TxRx} denotes the distance between Tx and Rx. The UWB free-space propagation – the total attenuation between a lower and an upper frequency f_{l} and f_{u}, respectively – is