Electromagnetics-Related Aspects of Signaling and Signal Processing for UWB Short Range Radios*

A.O. Boryssenko[1], D.H. Schaubert[2]

Antenna & Propagation Laboratory, University of Massachusetts,
Amherst, MA, USA ([1]boryssen@ecs.umass.edu, [2]schaubert@ecs.umass.edu)

Abstract

A numerical model of the UWB channel created by two dipole antennas is developed to characterize the antennas and the whole channel using system level concepts such as transfer functions in the frequency domain. This model is based on rigorous numerical electromagnetic (EM) analysis, thereby enabling predictions of the channel performance under impact of different antenna geometries, their spatial arrangements, and disturbance caused by diverse factors observable in practical links. These studies of channels address to a number of important issues in electromagnetic-related aspects of UWB signaling schemas and signal processing. First, pulse shaping is developed to support signal transmission across the channel with necessary temporal and spectral features, and high efficiency of energy transmission. To this end, several realistic antennas and practical short-range radio operational scenarios are considered. Second, a system-oriented approach is presented through antenna-signal-circuitry co-design. Finally, overall system performance and hardware complexity of signaling including receiver processing are evaluated.

1. Introduction

Recently, a number of valuable ways have been proposed to support high-data rate transfer in short range UWB channels and to achieve high spatial resolution with imaging capabilities in UWB radars [1-3]. In particular, high-potential pulsed signaling is predicted for time-hopping spread-spectrum employing impulse signal technology [3-4]. Such and other system-oriented UWB applications require signals with bandwidth ranged

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from a few hundred megahertz to several gigahertz wide or, equivalently, pulses of nanosecond or subnanosecond width in time domain. Those signals can be severely distorted across UWB channels even in a free-space line-of-site (LOS) mode. The benefits and shortcomings in UWB signaling for diverse purposes are widely discussed in literature for different UWB systems, operational environments, antenna geometries, signaling schemas, modulation formats, etc. [1-4]. We are concern in this study with some system-oriented aspects of this generic problem, viz. impact on pulsed transmission efficiency of underlying electromagnetics phenomena in links created by simple canonical dipole antennas, matching to an emission regulation, complexity of realizations to support signaling schemas in both the transmitter and receiver, and signal processing at the receiver end.

To create efficient signaling schemes in UWB channels, an accurate description of the channel is needed. For UWB systems, it is especially important to accurately model the impact of real dispersive antennas and the overall physical mechanisms of transient radiation, reception and scattering. As a result of such underlying physics, any signal that is collected by the receiving antenna, usually needs to be processed in some manner to obtain the desired features [1-4]. In turn, the nature of the required signal processing depends on both the antennas and propagation characteristics of the UWB channel [4].

However, the signal processing models of the antennas and the propagation in UWB channels rarely include explicit and accurate electromagnetic effects. Rather this complex physics is introducible through some approximating assumptions like derivative model for signals across the link [5-8], simple mathematical pulse shapes to model signals in channels like Gaussian monocycle and others [2-4], or plane waves to drive the receiving antennas through incident fields [8], etc. Although electromagnetic analysis of antennas and propagation is a mature research topic with a vast amount of special literature, its connection to the signal processing algorithms forms a partial picture only [9-11]. A deeper understanding of the antenna and propagation effects and signal processing will be beneficial for better modeling and design of UWB systems. For example, waveform transformations across UWB channels can be interpreted as a natural processing applied to the pulses for changing gradually their shapes as they travel across the UWB channel. This insight is helpful for reducing complexity of the receiver processor as demonstrated in this paper.

Stated differently, any UWB system has to be designed based on precise accounting for the above electromagnetic factors because of their strong impact on signal processing algorithms and their implementation with the help of system hardware and software. The purpose of this work is to study electromagnetic aspects of the signal processing applied to UWB radios based on accurate prediction of physical behavior for antennas creating a UWB link. The ultimate goal is to improve the behavior of signal processing algorithms in real-world-like situations for short range UWB radios. One more purpose of the current study is to establish a full-wave numerical simulation approach for the characterization of an UWB Tx-Rx antenna system in an attempt to design better UWB short range radios of reduced complexity. All results presented here assume an ideal synchronization (timing) in the UWB channels, which is a challenging issue itself [4] but beyond the scope of this paper.

The simulated data are given for the band around 1-3 GHz that might be used in future experimentation. Specifically, modern available digital ICs operates at the clock frequencies up to 6 GHz [2] corresponding to the Nyquist frequency for the band with maximum frequency 3 GHz. Also, the band 1-3 GHz is much suited for operation with "through-matter" propagation that enables a number of important applications. The presented results are easy to be scaled for any 3:1 frequency band, e.g. the FCC allocated 3-10 GHz.

The rest of the paper is organized in the following order. In Section 2, we discuss the numerical approach used to derive an accurate full-wave numerical model for LOS links formed by two antennas. In Section 3, we develop a pulse shaping technique that seems efficient in terms of system overall performance and low-complexity implementation. This signaling technique follows from our early reported results [12,13] to deal with antenna-signal co-design. Some practical examples of such signaling are explained throughout Section 4. Finally, in Section 5, some numerical results are presented for evaluation of hardware complexity including the receiver processor. At the end, some conclusions are presented in Section 6.

2. Channel Model with Dispersive Dipole Antennas

2.1. General Channel Modeling Methodology

From a system design perspective, the transfer function in the frequency domain or the equivalent impulse response in the time domain can be used to predict all changes in shapes and spectra for the transmitted and received pulses in the link between transmitting and receiving antennas. Furthermore, design of a matched filter receiver demands a clear knowledge of the shape of the pulse at the receiving antenna terminals [1-4].

A. Simplified Analytical Models vs. Accurate Numerical Full-Wave Models

In many papers on UWB topics including most of early publications [5-8], the signal transformation in the UWB channel is considered though a number of simplified analytical models. For example, the transmitted signal is mathematically expressed as the first derivative of the signal waveform applied to the transmitting antenna. In turn, the voltage induced at the terminal of the receiving antenna is the first derivative of the incident field waveform or the second derivative of the transmitter driving signal, and so on. However, the relationship between the above physical quantities is not of such a simple mathematical form of derivative, double derivative, etc. The relationship can be complicated [14] and must satisfy the time-domain version of reciprocity [15]. Other historical simplifications include the use of a set of simple mathematical pulse shapes to describe signals in the UWB channels. Such signals as Gauss pulse, first derivative Gauss pulse, Gaussian monocycle, Rayleigh pulses and other similar ones are widely employed as signals across UWB links [2-4]. Clearly, these signals are well suited for transformations based on derivatives but they are not adequate to design high-performed links, as demonstrated in this paper.

B. Time-Domain vs. Frequency-Domain Numerical Full-Wave Modeling

Evidently, the antenna and channel characteristics may be described in either the time or frequency domain, and they are unambiguously related through Fourier transform. Because of the very wide bandwidth, EM simulation in the time domain may seem more appropriate compared to the frequency domain [2,14]. However, frequency-domain analysis can be more suitable for links created by a number of objects arbitrarily spread over a scene because simulations in the time-domain require explicit accounting for time delay for EM interactions between such partitions. Conversely, frequency-domain full-wave EM solvers account simply for such delays through phase factors without any extra computational cost.

Practically, the signal transformations in the UWB channels are complex functions of several parameters related to the type of used antennas, their spatial arrangement, and others that can be only numerically predicted through a full-wave electromagnetic simulation [2,3,14,17]. Meeting this demand, we developed several numerically accurate and efficient tools to simulate isolated antennas, antenna arrays, whole links, and general scenes with multipath effects. Also, our simulation tools allow exploration in the frequency domain a number of link scenarios with different antenna types, their orientation, link disturbance, etc, including parametric analysis for the above factors.

2.2. Numerical Model of UWB Channel with Two Antennas

Some sample geometrical configurations of antennas that can be considered for using in UWB communication as are shown in Figure 1. To illustrate the key results of this paper, we explore a simple link structure with two omnidirectional antennas, Figure 2a, that operate in LOS free space mode and can be arbitrary separated with respect to each other. The case of high gain antennas like TEM-horns, Vivaldis, reflectors and others [18,19] that can be used in UWB channels are not studied here. The link can be represented with a simple equivalent circuit, Figure 2b, that illustrates the key components of its transfer function. Specifically, the transmitter (Tx) is presented just by the voltage generator V_G

with internal resistor R_G (or characteristic impedance of transmission line) while the receiver (Rx) is the load resistor (line impedance) R_L only with the voltage drop V_L The vector radiated field, $\vec{e}_{Rad}$ can be computed for any spatial observation point in antenna's surrounding space. There are two types of the transfer functions, viz. the link transfer function for energy transmission between transmitting and receiving antennas and the field transfer function for energy delivered from transmitting antenna to the electric field at a given spatial point. Such functions can be numerically computed through a full-wave EM solver like Method of Moment, FEM, FDTD or others. Both the functions are important to predict the link features to be matched with a number of operational and regularization demands.

The link transfer function is expressed in the frequency domain versus the radian frequency ω as the ratio of the voltage at the receiver load, $V_L(\omega)$, to the transmitter driving voltage, $V_G(\omega)$, with the free-space transfer function, $H_0(\omega, R)$, removed.

$$H_{LG}(\omega, R) = V_L(\omega) / V_G(\omega) / H_0(\omega, R) \qquad (1)$$

The free-space transfer function $H_0(\omega, R)$ contains a phase shift due to the propagation time and the energy divergence in free space versus the distance R and the radian frequency ω (or wave number $k = \omega / c$, where c is the free-space speed of light)

$$H_0(\omega, R) = \exp(-jkR) / R \qquad (2)$$

Note the distance R is defined for clarity as the distance between the transmitter and receiver reference points, typically the antenna terminals. Similarly, the field transfer function is defined with respect to the radiated fields in space. In general, this is a vector function, but we consider its scalar component that is related to a preferred polarization. Thus, the scalar transfer function for the principal radiated components of the vector radiated field, $\vec{e}_{Rad}(\omega, R)$ at a given spatial position is expressed as:

$$H_{FG}(\omega, R) = e_{\text{Rad}}(\omega, R) / V_G(\omega) / H_0(\omega, R) \quad (3)$$

In this case, the parameter R is the distance between the port of the transmitting antenna and a given spatial observation point. Angular dependence is not shown in (1) and (3) to reduce notational complexity, but it is implicitly assumed and can be used anytime if such a need exists. Also, the vector nature of the transfer function (3) and polarization features of the radiated fields can be accounted for, if necessary.

2.3. Channel Transfer Function Examples

The transfer function involves the basic characteristics of both the antennas, i.e. dispersive features, impedance matching, radiation and reception properties, matching in polarization, gain, pattern etc. As well, possible blockage, multipath, and near-field disturbance can be included in the transfer function. Broadband antennas can support a broader band signal with higher efficiency, so the transfer function provide a preliminary estimate of antenna's ability to perform in the UWB link.

An analogy between the UWB two-antenna channel and a filter can be helpful to realize some fundamental features. For example, link may be required to support "flat" magnitude (gain) and "linear" phase (group delay) of the link transfer function over a maximum band permitted by the antennas [14,16]. Mathematically, the filter gain, $A_{LG}(\omega)$, and group delay time, $\tau_{LG}(\omega)$, are given by [20]:

$$H_{LG}(\omega) = A_{LG}(\omega) \cdot e^{j\theta(\omega)} \quad (4a)$$

$$\tau_{LG}(\omega) = -d\theta(\omega)/d\omega \quad (4b)$$

where the dependence on the distance R is omitted for simplicity. Obviously, if the filter has a nearly linear phase response and the gain is nearly constant in the band, pulse distortions will be minimized over the channel. If delay and gain vary with frequency, the transmitted pulse will distorted by the channel. It was demonstrated that real antennas do not possess FIR-like filter symmetry for transmission free from distortions [14,20]. Thus, knowing the transfer function, viz. the gain and time delay in the band allows estimating the pulse distortions in the channel.

We do not analyze furthermore this fundamental regularity. Rather we consider the gain magnitude $20 \cdot log_{10}|A_{LG}|$, and group delay time τ_{LG} for several demonstrative link cases. This consideration presents the potential channel properties must be properly exploited on the next design step when a particular signaling schema is used in the UWB channel. Figure 3 plots the link transfer function for several antennas sketched in Figure 1. Specifically there are tow groups of antennas: axially-symmetrical antennas such as very thin wire, 1-cm-diameter cylinder, 5-cm-diameter bicone, and 10-cm-diameter bicone; flat dipole structures such as flat strips of 0.5-cm and 3-cm wide and bowties of 5-cm and 10-cm wide. All the antennas are the same 15-cm length but diverse geometry. Based on the criteria of flat gain and constant group delay in the 1-3 GHz frequency range, we conclude that flat antennas like wide flat antennas like wide strips and bowties demonstrate better suitability that the volumetric bicones.

Figure 4 presents the effect of variation of the link transfer function versus disturbance cased by variable distance between two antennas forming the link. Two cases are shown there, viz. the 15-cm-long very thing wire and 15-cm-long and 10-cm-wide bowtie. The distance between the two antennas in the link is gradually changed from 15 cm to 15 m. At a distance of 15 cm, the antennas operate in their "near-field" region. The gain variations are small while the group delay time is nearly constant versus the distance.

More problems for link robustness is caused by the angular orientation between antennas, which leads to considerable variations for both the gain and group delay time, Figure 5. Thus, angular orientation would likely cause considerable pulse distortions. Note that magnitude of variations is slightly less for the bowtie dipole compare to the thin wire.

2.4. Some Antenna and Signal Design Considerations

The effect of antenna geometry is not much addressed in this paper but some conclusions can be done based on above examples. Ideal antennas should faithfully replicate the transmitted pulse at the receiving end in the UWB channel. However, it is impossible because of the underlying physics of transient electromagnetics illustrated by the simulated data. Thus, the designer must design/use antennas to limit the amplitude and group delay distortions below a threshold that will ensure reliable system performance. The antenna features, e.g. in Figure 3, present the potential limit that the designer has to properly use by creating a proper signaling schema. Because the link with respect to signals behaves as a filter any such signal has to be matched to this channel. We address in detail this apparent idea in the following paper sections.

3. Antenna-Signal Co-Design for UWB Channel

We consider signaling in the UWB channel with two omnidirectional antennas at the physical level of implementation for transmission of a single pulse between the transmitting and receiving antennas. First, we analyze several known approaches for pulse shape controlling in pulse radiation and reception modes. Second, we develop an approach that creates signals "matched" to the channel via a regularized inverse of the channel transfer function. Finally, we specify a few channel metrics to evaluate achievable performance.

3.1. Pulse Shaping Techniques for Antennas and Links

Over a sufficiently wide bandwidth, all antennas exhibit dispersion and, therefore, distortions of the transmitted/received waveforms. Recalling the analogy to filters as mentioned above, an assessment of the antennas and the signal should be performed comprehensibly, accounting for their impact on UWB radio systems. As in the case of circuit filters, the antennas' impact on pulse shape can be treated as a signal-processing component and be employed a priori in design of receiver processors. Several approaches are presented in literature for pulse shaping, mostly for transmitting antennas. In the discussion that follows, we do not consider subband techniques [2] that are sometime used to divide the UWB spectrum in multiple wide bandwidth channels. We focus the discussion of signaling techniques that are useful for bandwidth 3:1 or greater.

A. Resistive Damping

Resistive damping of pulsed antennas has been used for many years ago to create an appropriate wideband response [21]. It is possible to deal with discrete resistive loading at the antenna's terminals or continuous resistive tapering along the antenna surfaces. However, this option is not acceptable for many UWB devices, which must be highly efficient due to limitations of battery power. Also, resistive loading of the antenna lowers receiver sensitivity.

B. "Mathematical" shapes

Due to simplicity of analytical description and manipulation, a family of Gaussian, differentiated Gaussian, Rayleigh and other such pulses is widely used as basic source waveforms in UWB systems [2-4,16] as mentioned above. Despite their apparent simplicity, such waveforms are difficult to create with real pulsers and dispersive antennas. Also, these waveforms allow only limited possibilities to conform simultaneously spectral and temporal signal constraints [2].

C. Predistortion of transmitter pulses

Predistortion of the generator waveform is capable of producing signals with energy concentrated in a narrow time interval [22]. For example, pulse predistortion such as E- and K-pulse shaping techniques were extensively explored in the past for the purposes of target recognition [21]. Traditional E- and K-pulse techniques are applicable to the pulses backscattered from radar targets. The characteristics of transmit and receive antennas are included in the analysis [21]. A relatively simple asymmetrical triangle pulse has been found to suppress the inherent resonances of a transmitting dipole and to produce a fairly short pulse of radiated energy with little late-time ringing [24].

D. Predistortion to channel transfer function

Scientific and engineering applications in seismology, medicine diagnostic, nondestructive testing, and subsurface radars benefit from the use of deconvolution, inverse filtration, spectral balancing, time-reversal processing, channel equalization and predistortion, and so on, e.g. [25,26,27]. Obviously in the case of electromagnetics, both the transmitting and receiving antennas must be involved in the pulse shaping, for example, through a variational approach [28], nonlinear optimization technique [23], time reversing [27] and a number of others. Since the use of the predistorted pulses provide obvious advantageous for practical implementation of UWB systems, we develop below a hardware-oriented technique, which seems to incur little or no penalty in the complexity of the transmitter and receiver while providing improvements in UWB link performance.

3.2. Pulse Shaping Through Inversion of the Channel Transfer Function

Our purpose is to use as much as possible the available channel potential presented in (4) via a pulse predistortion. Because the choice of antennas constitutes the potential limit of the channel, we seek to control unavoidable transformations in signal waveforms and spectra through channel equalization rather trying to minimize the distortions. To this end, the transmitting antenna driving voltage in frequency domain $V_G(\omega)$ or in time domain $v_G(t)$ has to anticipate properly in advance all principal modifications happen when signals travel across UWB links. Such driving pulses can be defined through deconvolution of channel impulse responses in time domain or inversion of channel transfer functions in frequency-domain, which seems numerically easier [25,26]. The later case is generally expressed through Inverse Fourier Transform (IFT), e.g. for the link transfer function $H_{LG}(\omega)$:

$$v_G(t) = IFT\{1/H_{LG}(\omega)\} \qquad (5)$$

As such, the waveform $v_G(t)$ synthesized through (5) produces 'flat" power spectral density (PSD) for the signal at the receiver load. The same approach is applicable for the field transfer function, $H_{FG}(\omega, R)$, to meet an emission regulation. However, waveforms directly obtained through (5) are unnecessary complicated and difficult to be reproduced with simple generating circuitry. That is, that the inverse of $H_{LG}(\omega)$ is ill-behaved at the frequencies where the magnitude of the transfer function is very low and, correspondingly, the inverted values of the driving voltage are very high. Regularization and filtering of (5) is necessary to obtain useful results. It has been found that windows in the time and frequency domains are useful for pulse smoothing, time confining, and meeting some emission regulations and constraints:

$$v_G(t) = w(t) \cdot IFT\left\{W(\omega) / \left(H_{LG}(\omega) + \delta\left[H_{LG}(\omega)\right]_{BW}\right)\right\} \qquad (6)$$

where, *w(t)* and *W(ω)* are appropriate windowing functions in time and frequency domain [20] respectively, δ is a stabilization term for dealing with the extremes of the transfer function in the band of interest, *BW*. Some results of applying the pulse shaping (6) are given in Section 4 of the paper.

3.3. Some Figures of Merit for Pulse Transmission in UWB Channels

A key performance parameter for UWB system is signal-to-noise ratio (SNR), from which system characteristics such as false-alarm-rate for radar [1] and bit-error-rate for wireless communication [2-4] can be estimated. However, other considerations also enter UWB system design and evaluation. This section includes discussion of some figures of merit.

A. Energy efficiency characteristics

Because the primary goal of the UWB link system is energy transmission, the link transmission efficiency can be important. The energy efficiency can be derived as

$$\eta_{Link} = W_L / W_G \qquad (7)$$

where the quantities W_G and W_L are the energy available from the generator and the energy captured in the receiver resistive load, correspondingly. Their computation is trivial in time and/or frequency domain, e.g. [28].

B. Emission limits and regulations

Spectral emission regulation is a transmit antenna issue of UWB link design that is controllable with the help of the field transfer function (3). There are several national standards for interference avoidance and consistent coexistence between UWB radio systems and other radio systems of shared bands [2]. The closer the signal PSD conforms to the spectral mask, the more energy can be transferred within the same allocated frequency band. We will demonstrate suitability of the developed pulse shaping technique to satisfy such an emission regulation, e.g. FCC indoor mask.

C. Sharpness of pulse in the receiver load and/or spatial observation points

Sharpness of the signaling pulses is an important feature for efficient detection of signals that can be masked by noise and interference. In radars, a sharp pulse enables better range resolution, broader spectral target illumination and observation of more targets' shape-related resonances that makes easier extraction of desired target information [1]. At the same time, having spiky signals in indoor communication channels helps to resolve multipath signal components and to provide an efficient multipath mitigation [4].

D. Complexity of hardware/software implementation

This important issue is illustrated in Section 5 for several cases related to the transmitter and receiver front-end circuitry and the receiver processor. Specifically, we study a digital realization for the circuitry. As well, the issue to design a receiver processor, which can be either matched filter or correlation receiver, is addressed.

4. An Optimal Signaling for UWB Two-Antenna Link

We consider several cases to demonstrate some advantages of the proposed signaling with respect to signaling with a canonical Gaussian monocycle to meet several operational demands in the UWB channels.

4.1. Signaling Optimized Pulse vs. with Gauss Monocycle

As a reference case, the transfer of the Gaussian doublet through the link created by the bow-ties of 15 cm long and 10 cm wide is simulated, Figure 6. All curves of the upper row present from the left to the right normalized signals of transmitter, radiated far-field and receive. The lower row contains PSD for the same quantities in the same order. The computed link efficiency (7) is about -30 dB when spectral maximum of the Gauss pulse is matched to the maximum of the link transfer function. Figure 7 contains other simulated data for the same UWB link as above but with pulse shaping through inversion of the transfer function (6). Figure 7 illustrates the case when the flat PSD of the radiated field is supported that is resulted in pretty short pulses because of the intrinsic Fourier transform properties. The computed total link efficiency is about of the same -30 dB magnitude as the reference case, Figure 6. However, temporal and spectral features of both the radiated field and received voltage are dramatically improved because of (1) sharpening of all waveforms and (2) flattening of their spectral characteristics.

4.2. Matching to FCC Indoor PSD Mask

Figure 6 contains for reference the FCC PSD indoor mask [2]. When the transmit antenna and voltage waveform are specified as in Figure 6, there is no flexibility to comply with the FCC PSD mask. However, by using the frequency domain window in (6) compliance can be approximately supported in the presented pulse shaping technique, Figure 8, for any part of the signal spectrum even at its middle with a deep cut but the signal temporal shape is still well-confined in time. The given case in Figure 8 is just an illustration of the general idea and more accurate matching may be needed in practice.

4.3. Effect of Antenna Type

Figure 9 demonstrates how antenna geometry affects achievable pulse shaping and link performance. In this case, a wire-like dipole is involved that is of the same length as in Figures 6-8 but of the narrower width, i.e. 0.5 cm wide. Obviously, we expect degradation of UWB link features that follows from the link transfer function features, Figure 3. The total link efficiency with this antenna is about -10 dB less than for all above cases in Figures 6-8. Qualitatively, spectral shapes remain relatively flat and the radiated field and received voltage are confined to a short time interval. However, use of an inappropriate antenna significantly lowers the energy efficiency.

5. Implementation Complexity of UWB Link Transmitter and Receiver

5.1. Digital Transmitter and Receiver Front-Ends

An important question to be answered is suitability of the proposed pulse shaping technique for practical implementation in transmitter and receiver. Presumably, the hardware should be simple and based on low-bit digital ICs [2,4]. Digital circuitry is normally cheaper, less power consuming, repeatable, reprogrammable, easier to control, and directly provides interface to digital processing. Fewer bits allows use of simpler and cheaper ICs.

Figure 10 shows digitization of the synthesized pulse, Figure 7, with 3 bits for amplitude and one bit for sign. 150 ps time resolution is used, corresponding to about 6 GHz clock frequency achieved in digital ICs [2] as well the Nyquist frequency for this case. When the digitized signal is used for signaling in the same UWB link, Figure 11, instead of its analog counterpart, Figure 7, the features of the digitized UWB link are still acceptable. The same number of bits can be used for quantification of the canonical mathematical pulses such as Gaussian and Rayleigh signals but they do not demonstrate comparable features in pulse shaping and spectral control [16].

5.2. Receiver without Correlator

The complexity of receiver implementation needs to be estimated, also. Optimal filtering for communication and radar [1,2] requires using correlation receiver or matched filter for maximizing SNR. Thus, the correlation receiver is added in the schema of the UWB link, Figure 12b. Also, two signal templates are there, viz. in the transmitter, Figure 12a, and as reference signal in the correlation receiver, Figure 12b. Both of the template generators can be implemented through the low-bit direct digital synthesis (DDS) discussed above. However, the receiver in Figure 12b can be radically simplified in the case of the proposed pulse shaping for UWB link. In fact, the correlation receiver will be redundant if the antenna link itself supplies with a very short pulse at the receiver load, Figure 13a.

Comparing the input and output signals for the correlation receiver, Figure 13, proves this statement qualitatively. Moreover, simulation of for the case of the white Gaussian noise channel model shows that the processing gain is only a small fraction of dB. As such, the receiver can include only a sampling circuitry to catch the maximum of pulses at the receiver load, Figure 12c. Both systems, with and without correlator, require good synchronization.

6. Conclusions

The performances of UWB systems comprised of practical antennas have been analyzed with full consideration of the electromagnetic aspects of this problem. The model is based on accurate EM analysis, thereby including many of the antenna and channel characteristics encountered in practice. Since the dispersive properties of realistic dipole antennas are naturally incorporated in the numerical model, accurate prediction of channel features is possible. The model is also suited for analyzing potential signaling schemes, choosing among them those with positive impact on the overall channel performance and complexity of front-end circuitry and processing requirements including, for example, the correlation receiver processor.

The proposed co-design of antenna and signals creates signaling pulses with required features in time and frequency domain, good link budgets, potential to meet emission regulations, and so on. Also, low-complexity digital front-end circuitry can be used to provide such UWB signaling at both the transmitting and receiving ends of the UWB. For such pulses the product of time duration by bandwidth is nearly equal to one and their compressing in time can be achieved without use of correlation receiver rather. Furthermore, although not discussed here a combined numerical analysis is possible to simulate in the time-domain both the electromagnetic part, viz. antennas, and nonlinear electronics of the transmitter and driving circuitry.

In addition to the simple free-space propagation considered here, complex UWB links including nearby bodies, blockage, multipath, through-wall propagation, moving antennas, and other factors can be predicted through numerical simulation. Any degradation in the link performance can be estimated and minimized in some degree through adaptive pulse shaping, i.e. changing driving pulses to compensate signal distortions due to variable link environment. Finally, other operational cases of practical importance can be explored, e.g. combining geolocation and wireless modes.

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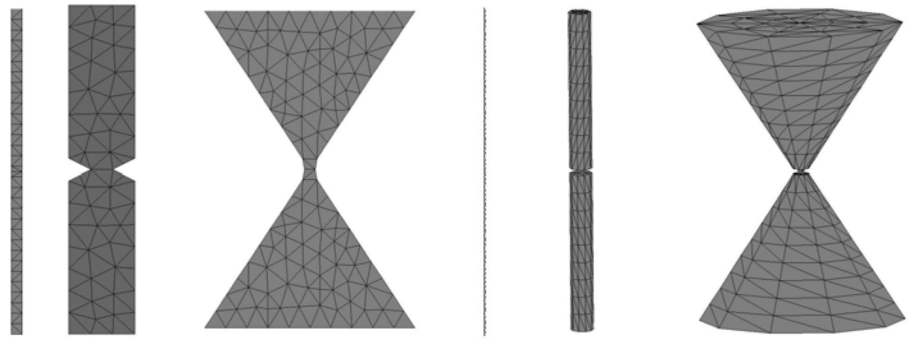
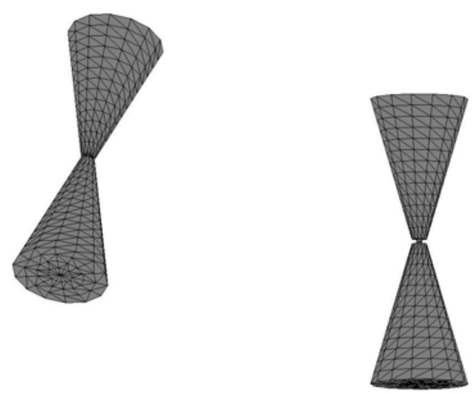
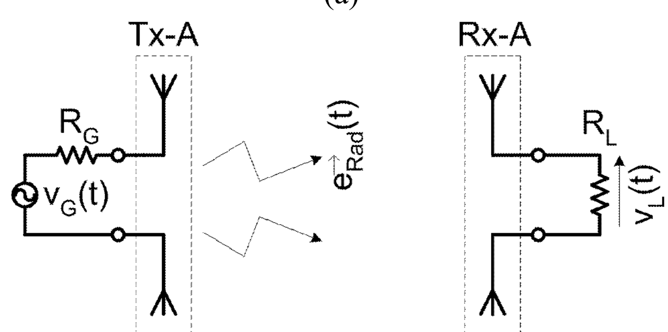


Figure 1

Planar and axially symmetrical dipole antennas including (from the left to the right): narrow and wide strips, bowtie, thin wire, cylindrical antenna and bicone antenna.



(a)



(b)

Figure 2

UWB link composed of transmit (Tx-A) and receiving (Rx-A) antennas: (a) link geometry created by two solid bicones; (b) time-domain schematic presentation with basic circuit and electromagnetic components.

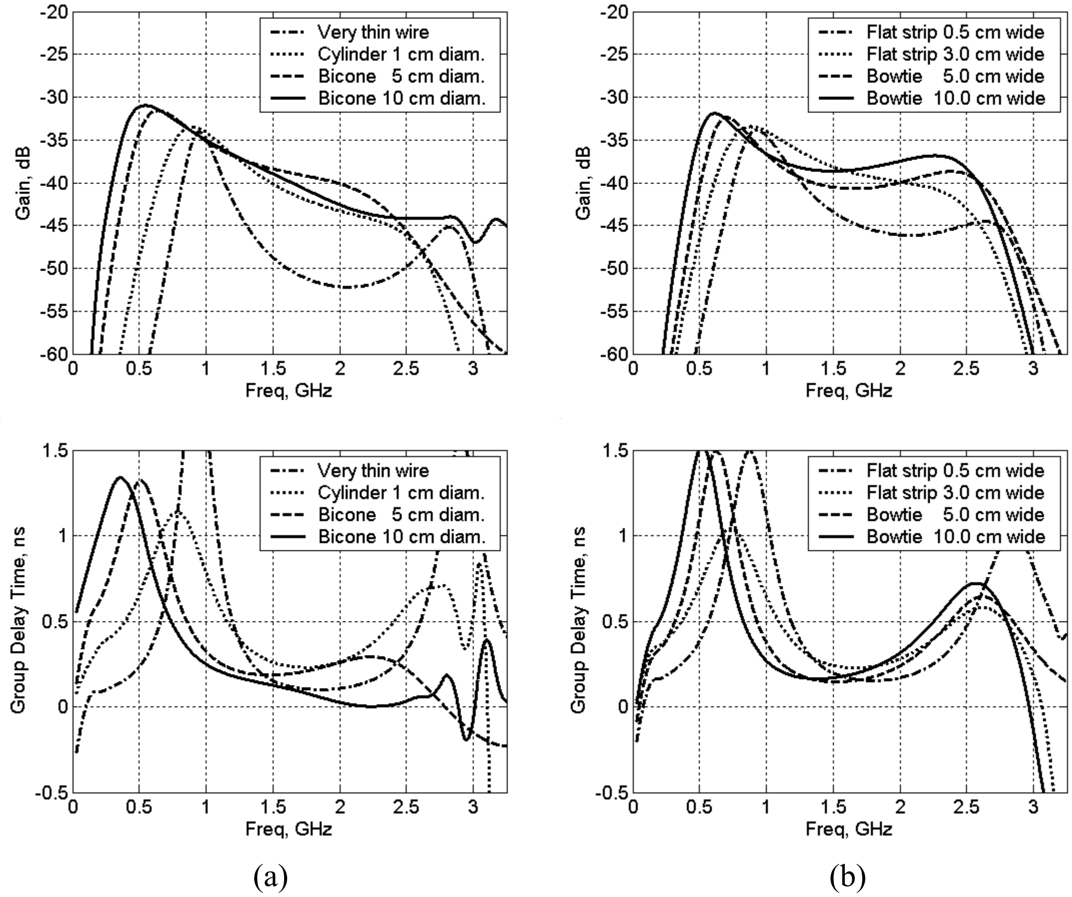
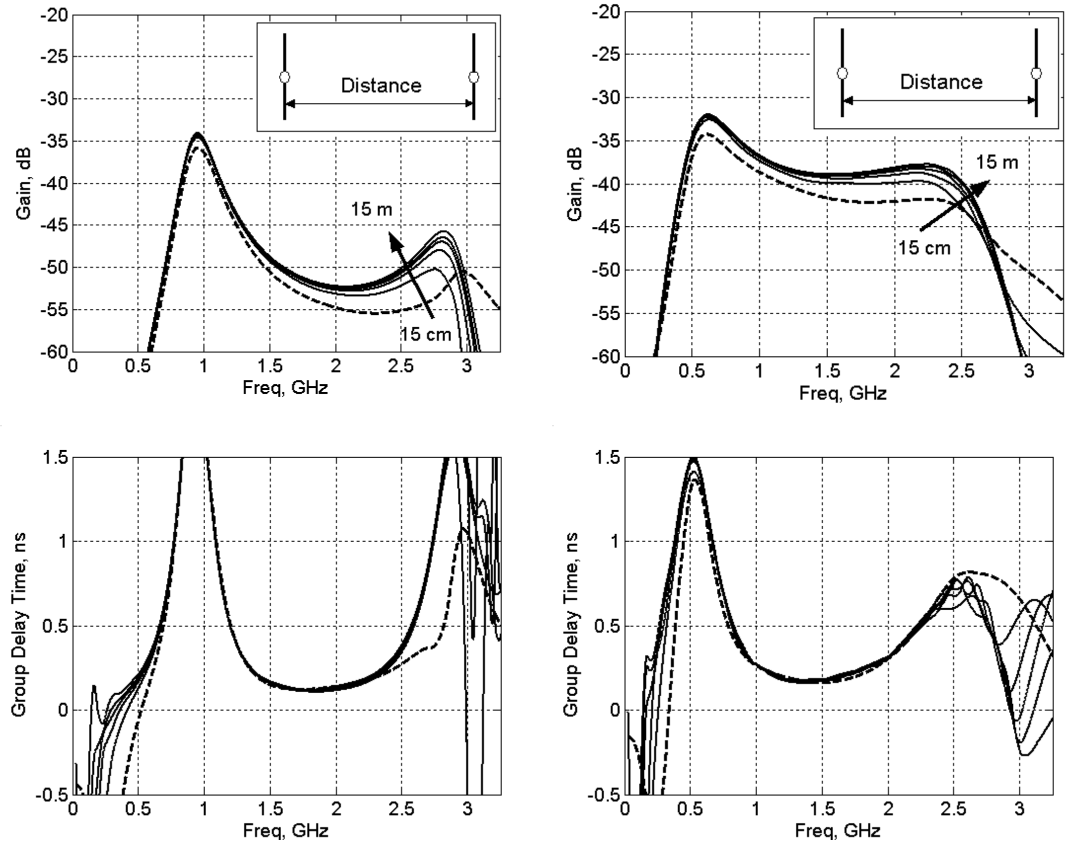


Figure 3

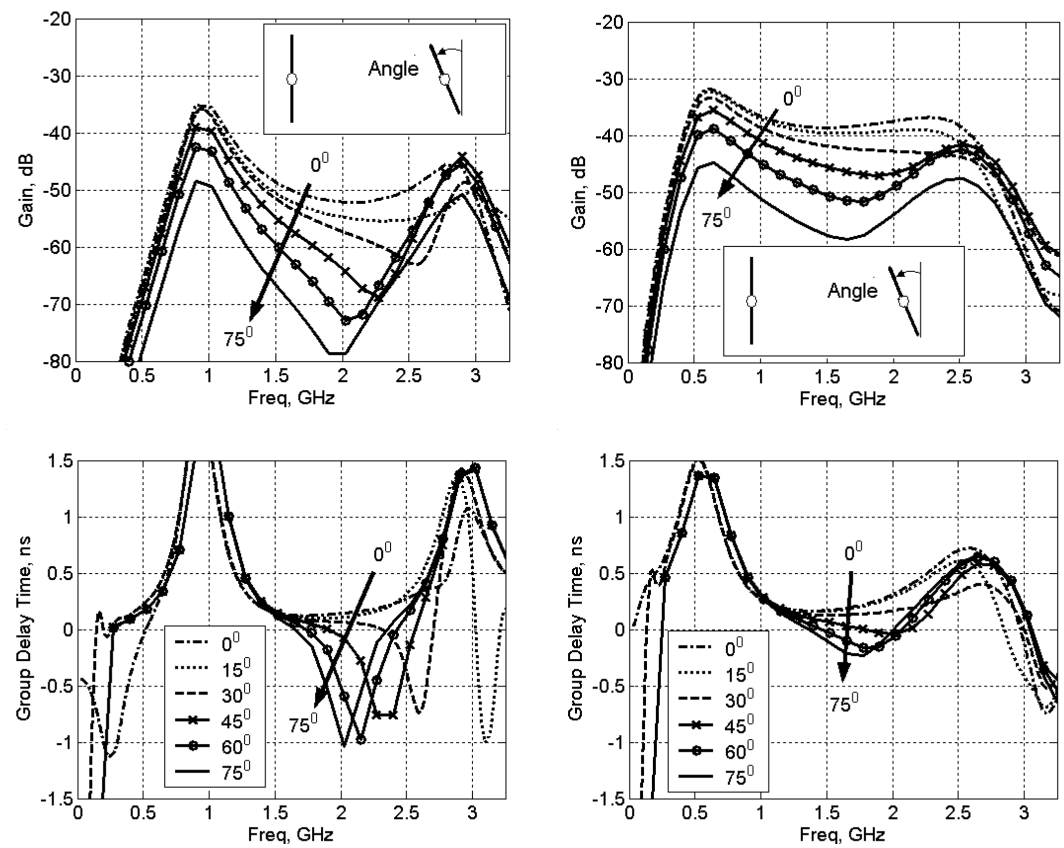
Link transfer functions, gain and group delay, for several 15-cm-long dipole antennas: (a) axially-symmetrical antennas, i.e. very thin wire, 1cm diameter cylinder, 5-cm diameter bicone, 10-m diameter bicone, magnitude; (b) flat antennas, i.e. 0.5-cm wide strip, 3 cm wide strip, 5 cm wide bowtie, 10 cm wide bowtie. $R_G = R_L = 100\ \Omega$.



(a) (b)

Figure 4

Variation of the link transfer function versus the distance between transmitting and receiving antennas gradually changed from 15 cm do 15 m for two different dipole antennas: (a) 15-cm-long very thin wire and (b) 15-cm-long 10-cm-wide bowtie. $R_G = R_L = 100\ \Omega$.



(a) (b)

Figure 5

Variation of the far-field link transfer function versus angular mismatching between transmitting and receiving antennas changed from 0^O to 75^O: (a) 15-cm-long very thin wire and (b) 15-cm-long 10-cm-wide bowtie. $R_G = R_L = 100\ \Omega$.

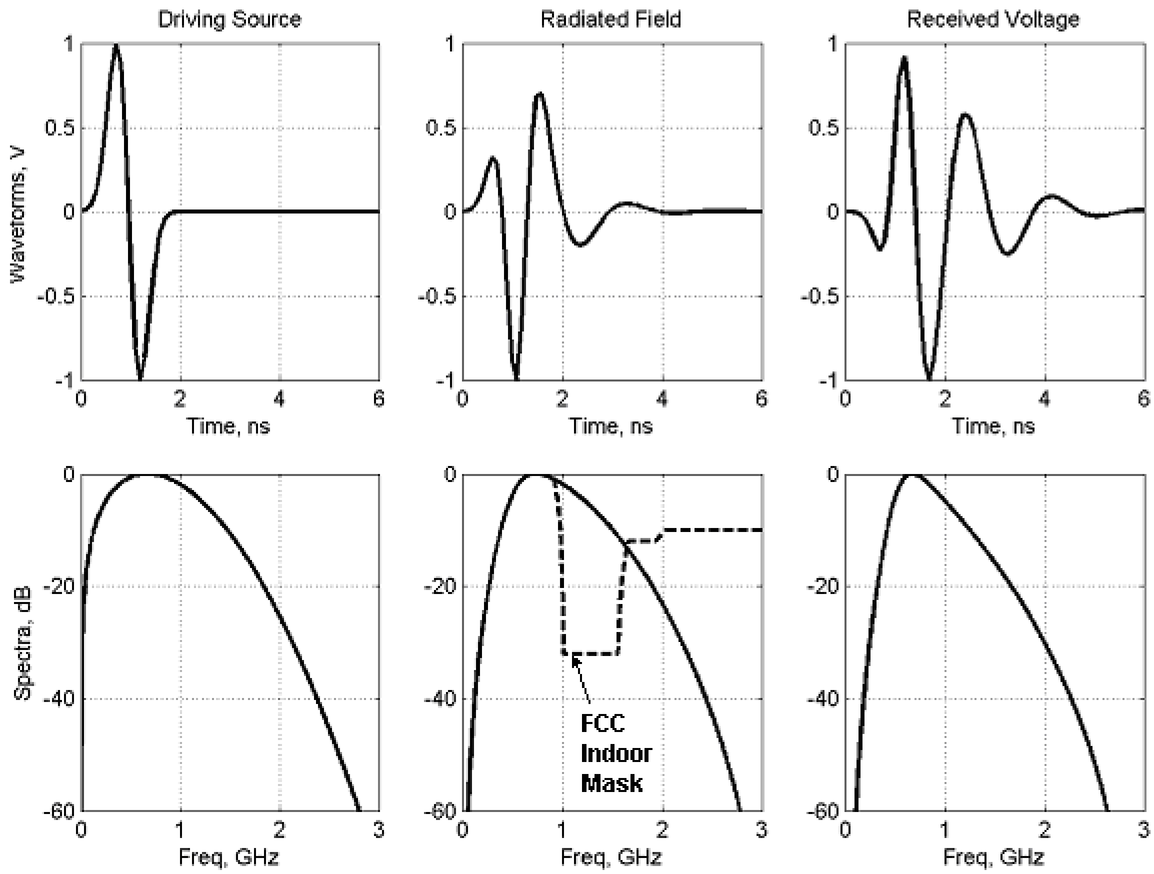


Figure 6

Using Gauss doublet signal for driving transmitting antenna in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles in far field. Total link efficiency is -30 dB. $R_G = R_L = 100\ \Omega$.

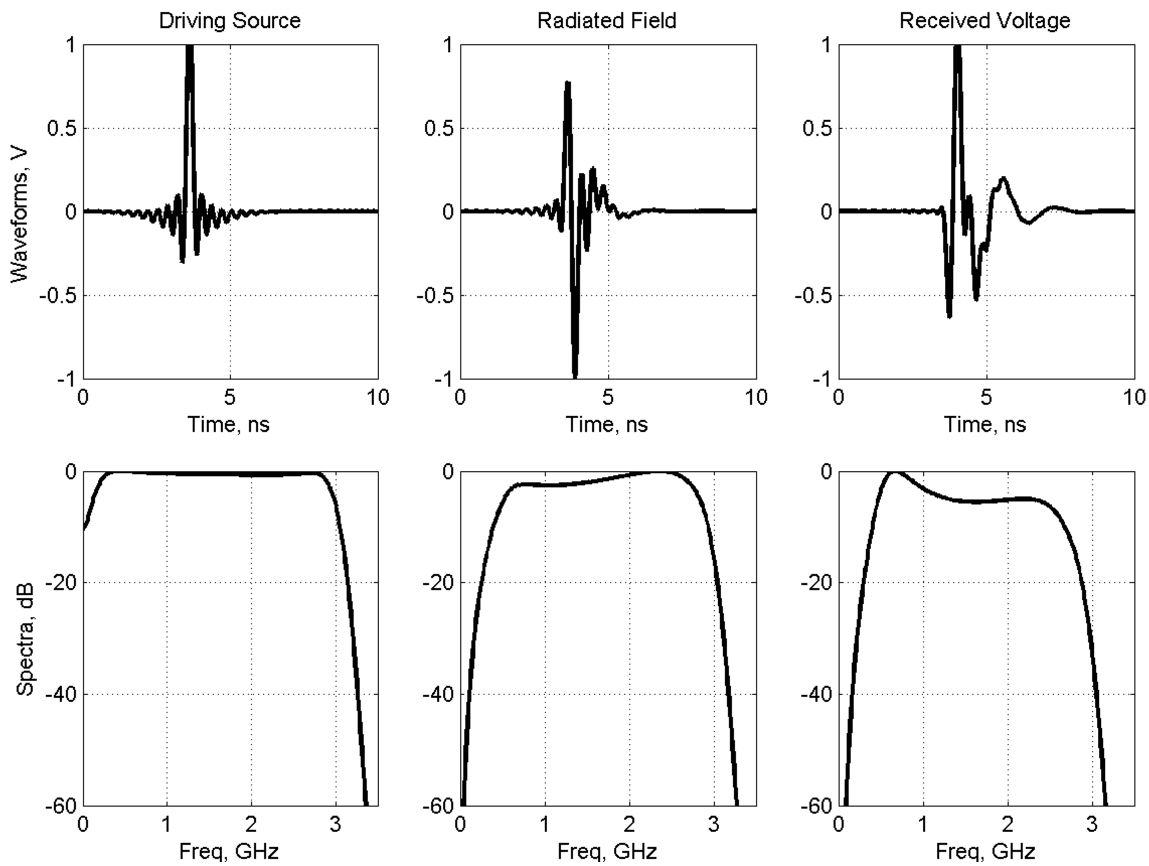


Figure 7

Pulse shaping through transfer function inversion in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles. Total link efficiency is about -30 dB. $R_G = R_L = 100$ Ω.

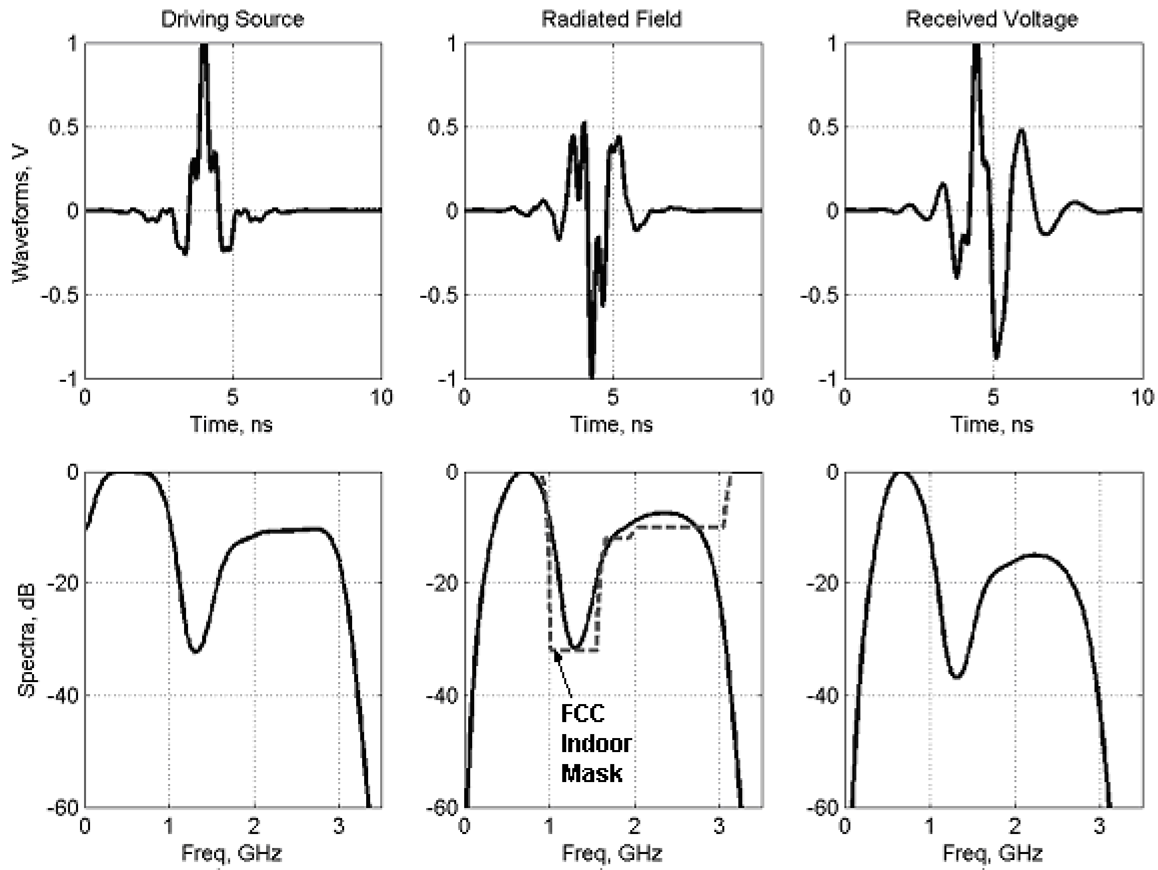


Figure 8

Pulse shaping through transfer function inversion and applying FCC indoor PSD mask in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles. Total link efficiency is about -30 dB. $R_G = R_L = 100\ \Omega$.

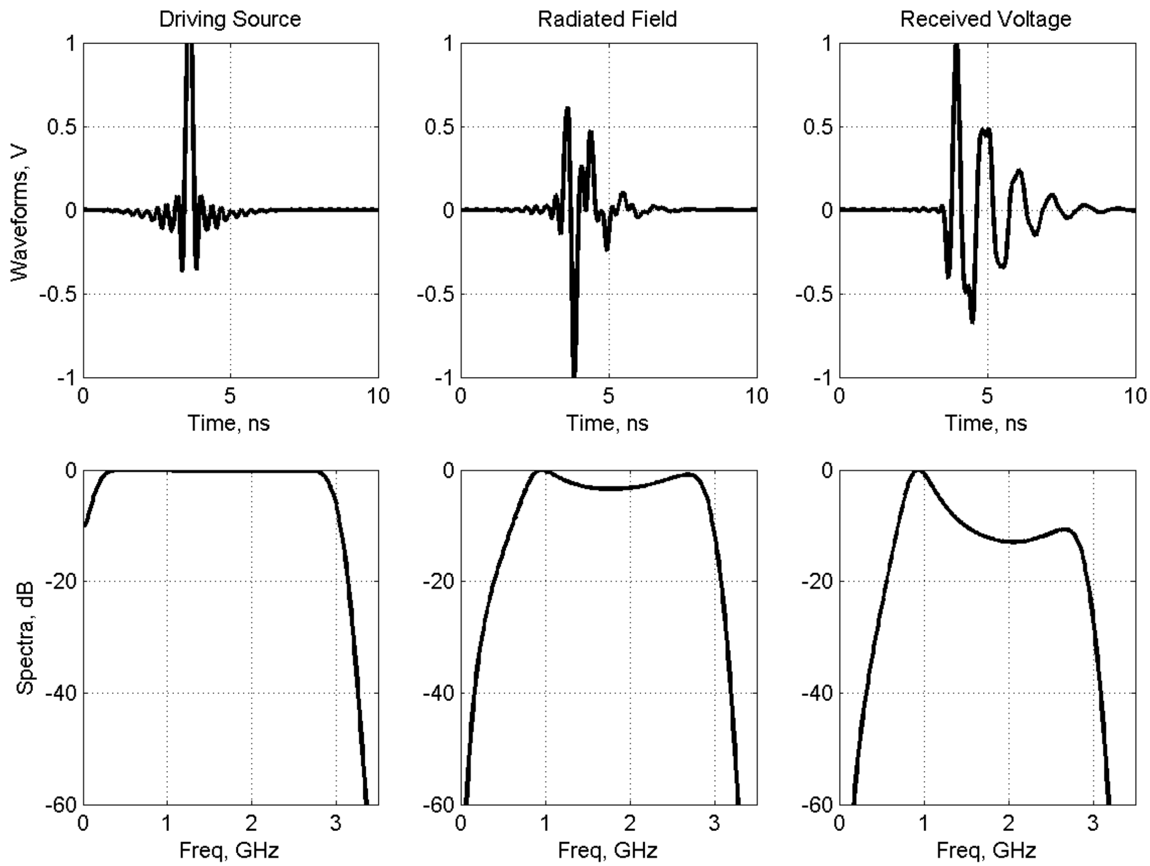


Figure 9

Pulse shaping through transfer function inversion for driving transmitting antenna in two-antenna UWB link with 15 cm long and 0.5 cm narrow wire-like dipoles. Total link efficiency is less than -40 dB. $R_G = R_L = 100\ \Omega$.

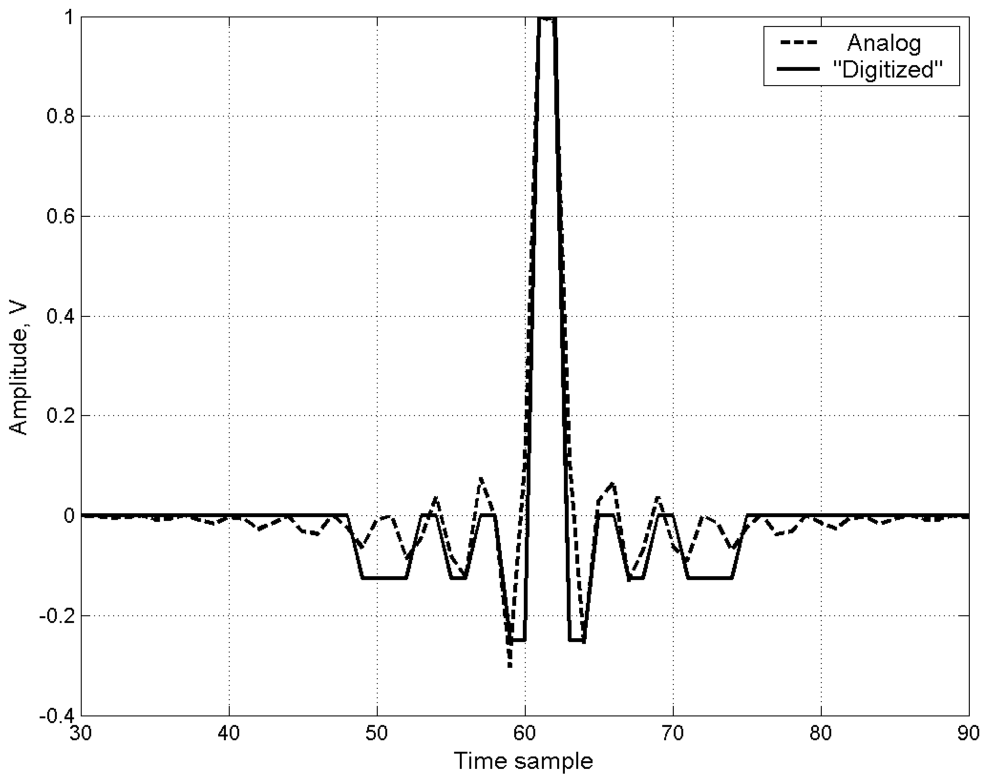


Figure 10

Digitizing driving pulse for transmitting antenna as in Figure 7 with 3 bit amplitude resolution plus one sign bit and 150 ps sampling in time.

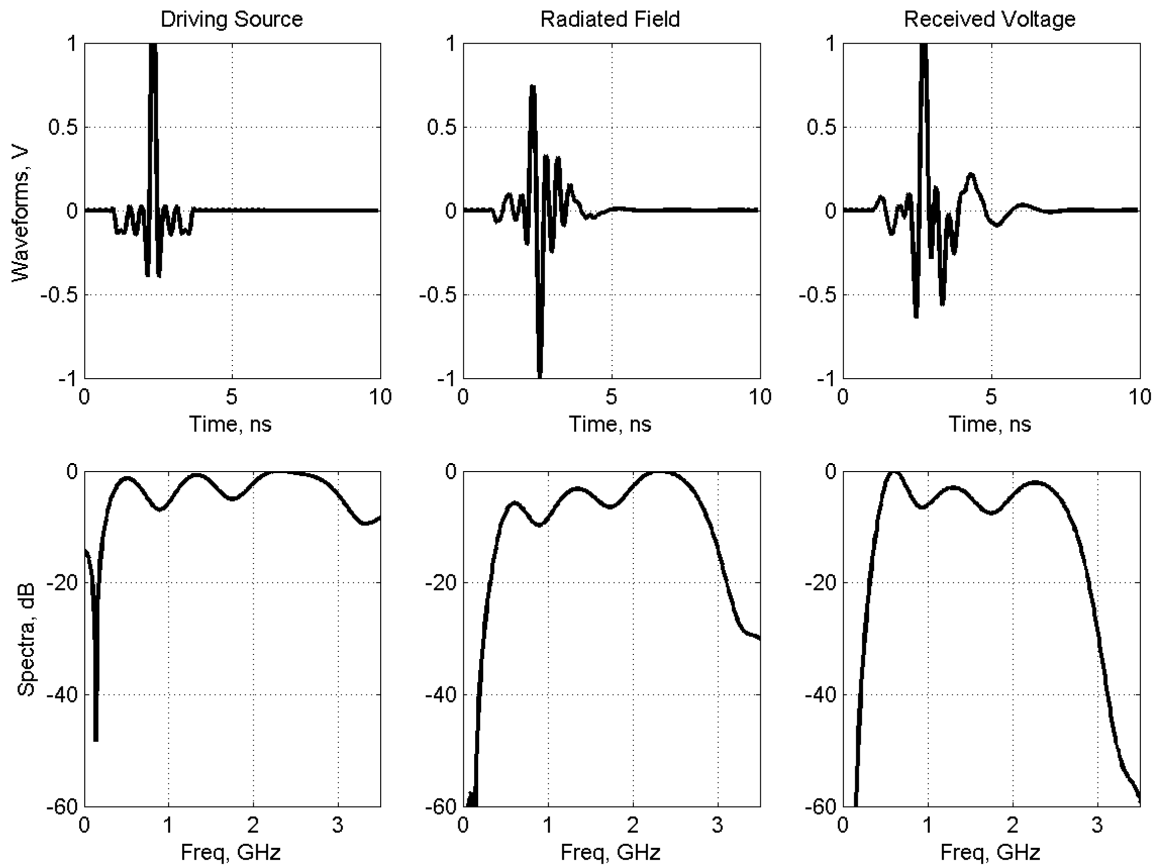


Figure 11

Pulse shaping through digitizing of driving pulse in accordance to Figure 7 in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles. Total link efficiency is still about -30 dB. $R_G = R_L = 100\,\Omega$.

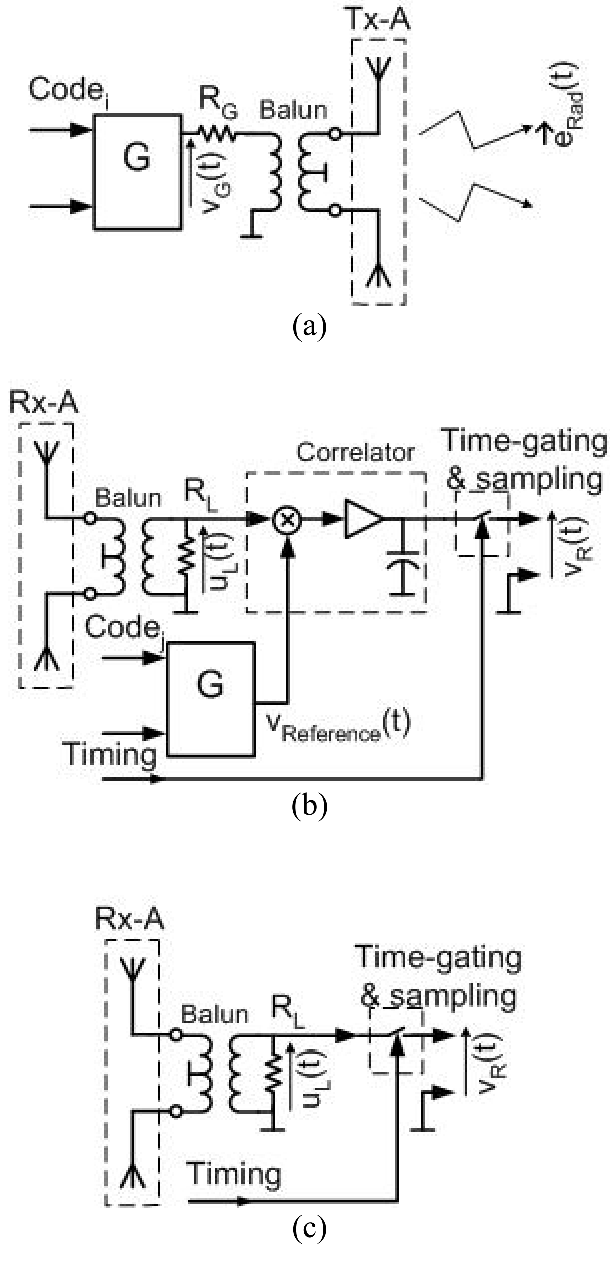
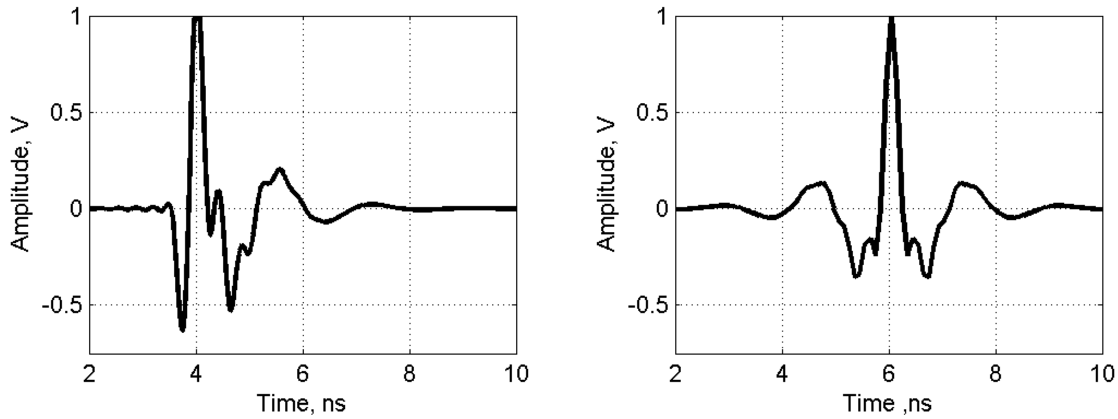


Figure 12

Functional diagrams of UWB link. (a) Transmitter with waveform template generator G. (b) Correlation receiver with signal template generator G in receiver. (c) Simplified receiver without correlator.



(a) (b)

Figure 13

Received signal at the input (a) and output of correlation receiver with pulse shaping matched to the channel predistortion. Processing gain of correlation receive is negligible, about 0.2 dB.