Optimal antenna and signal co-design for UWB antenna link

Short title: Optimal antenna & signal co-design

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Abstract—Antennas are a critical component of UWB link because of radical changes in signal waveform/spectrum on its way between transmitter and receiver. Antenna, circuitry and signals need to be designed collectively to send efficiently signals of pulsed energy between transmit and receiver antennas. Such a co-design approach is demonstrated in this work through pulse shaping for achieving required temporal and spectral features, high energy efficiency of link, meeting regulation on spectral emission and low-complexity (digital) front-end implementation.

Keywords: ultra-wideband, antenna, signal, transmitter, receiver, link

1. Introduction

General phenomenology and specific features of transient (pulsed) antennas are under tight attention of electromagnetic community for while in a broad range of computational electromagnetics, EMP, EMC, wireless, networking, sensor, radar and other applications [1-2]. In this study, we concern with efficient radiation of short electromagnetic pulses by transmitting antenna and their reception by receiving antenna.

Generally, antenna, circuitry and signaling components of UWB communication link needs to be co-designed to send efficiently signals of pulsed energy between transmit and receiver antennas under several rigid constraints. Such constraints can involve: (1) finite energy available from transmitter, (2) maximum energy efficiency of transmitter, (3) maximum available signal intensity delivered to receiver, (4) sharp shape of received voltage, (5) given power spectral density (PSD) of radiated field, (6) matching to some regulations on spectrum emission, e.g. the FCC indoor PSD mask etc. [2]. Such demanding and mutually conflicting requirements need to be implemented through using of (1) common dipoles, biconical, horn, tapered-slot and other antennas and (2) preferably digital off-shell ICs used in both the UWB transmitter and receiver front-end electronics.

Hence, a number of qualitative and quantitative parameters have to be in the focus for supporting the necessary signals with required spectral and temporal features at all critical points across the UWB link. In this work, we demonstrate a solution, which is numerically obtained through full-wave electromagnetic simulation for a link created by two broadband dipoles. For this purpose, a UWB link simulator is developed in the Antenna Laboratory of the University of Massachusetts that is based on the Moment of Moment technique in frequency and/or time-domain [3]. The presented results are received in the frame of the MURI NSF grant DAAD19-01-1-0477 “Short-Range Ultra-Wideband Radio” that is much appreciated.

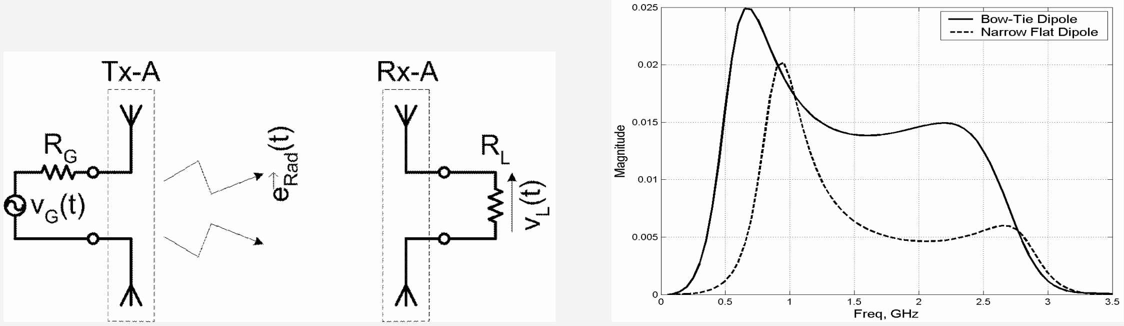
2. Pulse shaping for UWB antennas

Different geometrical configurations of antennas can be considered for using in UWB communication. We explore a simple link structure with two antennas, Figure 1b, where the transmitter (Tx) is presented just by the voltage generator U_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 U_L. As well, the vector radiated field, E_{Rad} can be computed for any spatial observation point.

The effect of antenna geometry is not addressed in this paper but some conclusions can be based on apparent properties of the link transfer functions. The transfer function is defined in frequency domain as ratio of the voltage at the receiver load, $U_L(?)$, to the transmitter driving voltage, $U_G(?)$. Also, other transfer function can be defined with respect to the radiated field. For illustration, Figure 1 b shows the link transfer function over the 0…3 GHz band for two dipoles of the same 15-cm length but different shapes, viz. 10-cm wide bow-tie and narrow 0.5-cm wide dipole. The free space propagation factor exp(-jkR)/R is removed in Figure 1 b. Sake simplicity but without loss of generality, the dipoles are in far-field, parallel each other and ideally matched in polarization and maximum gain direction.

Obviously, 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, near-field disturbance can be accounted in the transfer function. It is clear that inherently broadband antennas can support a broader band with much efficiency. So, the transfer function can characterize preliminary which antenna would perform better in the UWB link.

Several approaches are presented in literature for pulse shaping mostly for transmitting antennas like resistive loading that leads to lower energy efficiency. This mode cannot be acceptable, e.g., for battery-fed UWB devices. Other method of pulse shaping in transient antennas is under attention at the Antenna Laboratory of University of Massachusetts since the eighties [4]. This approach is based on accounting antenna inherent resonances and exciting by special pulses to avoid long time ringing. E.g., an asymmetrical triangle pulse for dipoles can be such a signal [5]. Both the transmitting and receiving antennas have to be involved in pulse shaping for UWB link [6]. Our key idea explored in the paper states that additionally both the antennas and signals need to be designed together.



(a) (b)

Figure 1. (a) Schematic sketch on two-antenna link with simplified transmitter as generator with internal resistance and receiver as just a resistive load. (b) Magnitude of free space far-field transfer function of two antenna link created by two dipoles of 15 cm length and 10 cm (solid line) and 0.5 cm (dashed line) wide.

3. Optimal co-design of antennas and pulses for UWB link

First, the full-wave Method of Moment is employed to compute numerically the transfer functions for the radiated field at a given spatial point and the received voltage in the receiver load. The former can be used for controlling spectral emission while the later is necessary to evaluate the link performance. Then, pulse transition between the antennas is explored for different pulse shapes extracted through inversion of the link transfer function, Figure 1b. Basically, the required driving pulse, $U_{Gen}(t)$, can be expressed as

$$U_{Gen}(t) = w(t) \cdot IFT\left\{W(w) / \left(T(w) + d \cdot \max\left[T(w)\right]_{BW}\right)\right\} \tag{1}$$

where $T(?)$ is the numerically computed link transfer function, IFT is Inverse Fourier Transform, $w(t)$ and $W(?)$ are appropriate windowing functions in time and frequency domain [7] respectively, d is stabilization term for dealing with the extremes of the transfer function in the band of interest, BW.

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 2. 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. Such and similar signals are widely considered in literature as basic UWB waveforms [2,8-9]. The computed total radiation and link efficiency [6] is about -30 dB when spectral maximum of the Gauss bicycle is matched to the maximum of transfer function, Figure 1b. This reference figure is used further as reference for different synthesized waveforms. Figure 2 contains also the FCC PSD indoor mask [2]. The authors [8] states that matching to the FCC PSD mask, in Figure 2, is acceptable but much better matching will be demonstrated below.

Figures 3-4 contain other simulated data for the same UWB link as above but with pulse shaping through inversion of the transfer function (1). Figure 3 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 2. 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. Additionally, the presented pulse shaping allows matching to the FCC indoor PSD mask, Figure 4.

Figure 5 demonstrates how antenna geometry affects itself on achievable pulse shaping and link performance. In this case, a wire-like dipole is involved that is of the same length as in Figures 3-5 but of the narrower width, i.e. 0.5 cm wide. Obviously, we expect degradation of UWB link features that follows from the transfer function, Figure 1 b. Clearly, this antenna demonstrates less efficiency to support the lower frequencies in the band. As a result, the total link efficiency with this antenna is about -10 dB less than for all above cases in Figures 3-4. Qualitatively, spectral shapes are not more flat and longer ringing takes place particularly for the received voltage, Figure 5. So, if an inappropriate antenna is used for UWB operation, it is possible to force it to operate somehow in a UWB-like mode but by the price of lower energy efficiency only. The figure of -10 dB loss comes primarily from the fail of antenna radiation efficiency.

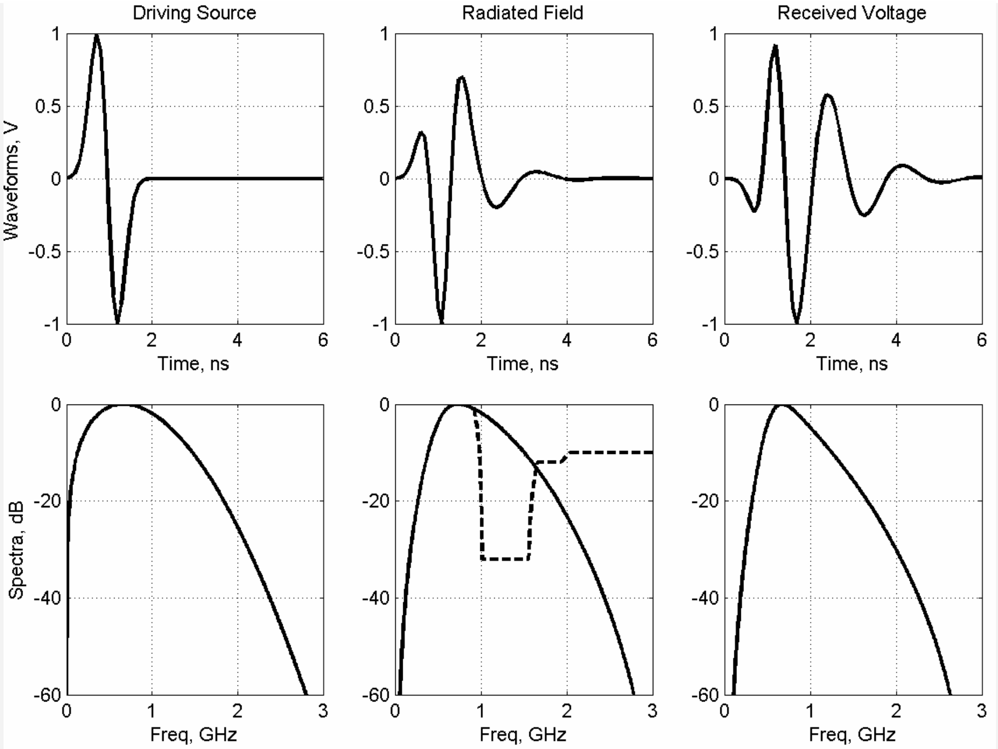


Figure 2. Using Gauss doublet signal for driving transmitting antenna in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles. Total link efficiency is -30 dB.

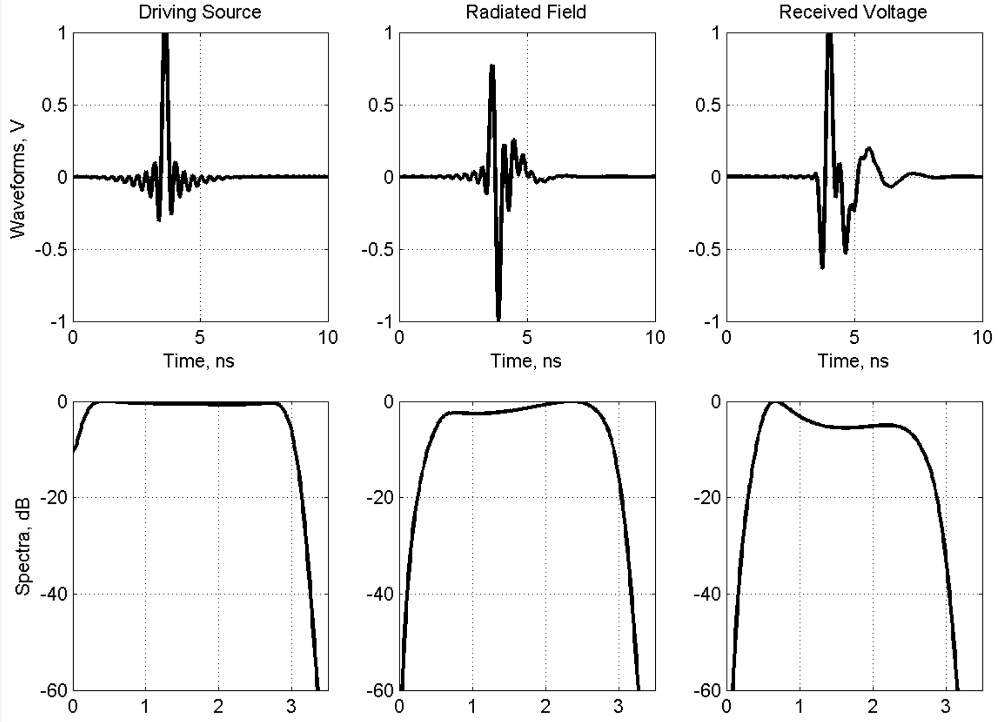


Figure 3. Pulse shaping through transfer function inversion in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles. Total link efficiency is about -30 dB.

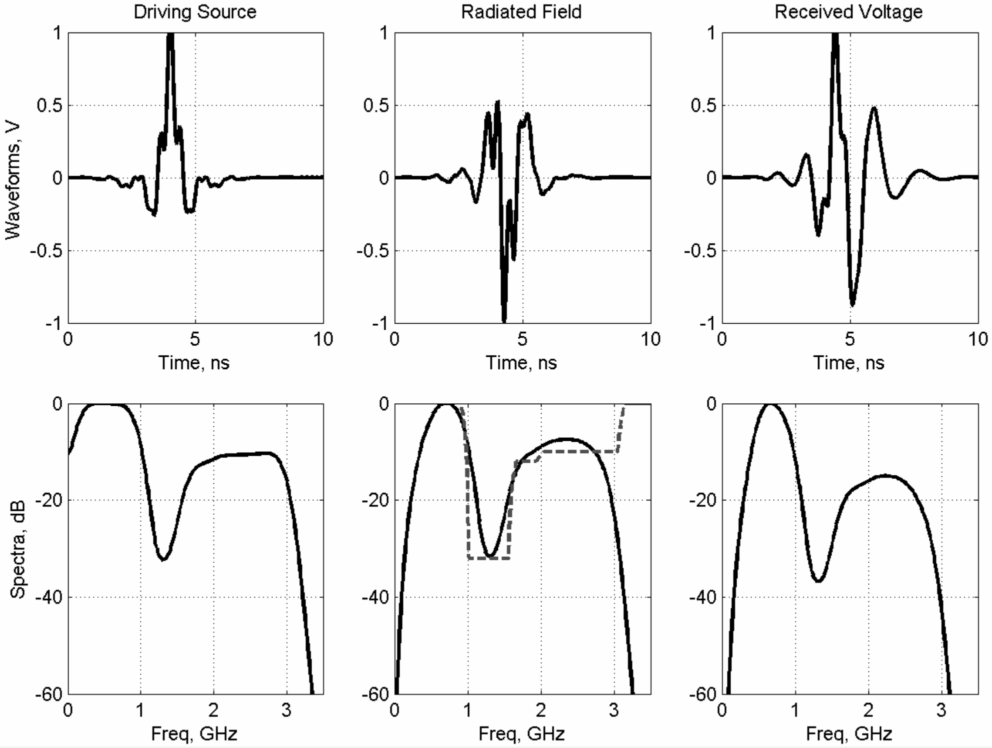


Figure 4. Pulse shaping through transfer function inversion and applying FCC indoor PSD mask in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles. Total link efficiency is about -30 dB.

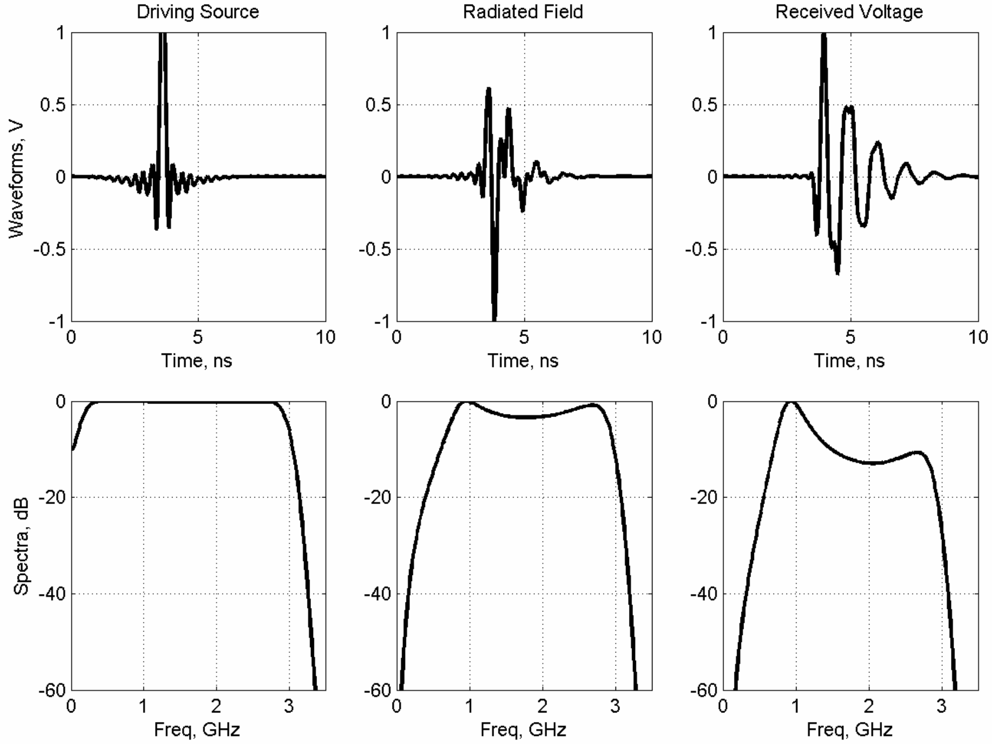


Figure 5. Pulse shaping through transfer function inversion for driving transmitting antenna in two-antenna UWB link with 15 cm long and 0.5 cm narrow wire-like dipoles. Total link efficiency is less -40 dB.

4. Simplification for transmitter and receiver hardware

An important question needs to be answered is suitability of the proposed pulse shaping technique for its practical implementation in transmitter and receiver. Presumably, the hardware should be simpler and based on low-bit digital ICs [2]. Digital circuitry is normally cheaper, less power consuming, repeatable, reprogrammable, easier controllable, directly providing interface to processing means and so on. The lower is the number of bits, the simpler and cheaper would be the used ICs. Figure 6 shows digitization of the synthesized pulse, Figure 3, with 3 bits for amplitude and one bit for sign. 150 ps time resolution is used that correspond 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 7, instead of its analog counterpart, Figure 4, the features of the digitized UWB link are still pretty acceptable. Note about the same number of bits is required for quantification of the canonical mathematical pulses such as Gaussian and Reyleigh signals but they do not demonstrate comparable features in pulse shaping and spectral control [8].

The complexity of receiver implementation needs to be estimated also. The optimal filtration theory for communication and radar [1,2,8,9] requires using correlation receiver for maximizing SNR. Thus, the correlation receiver is added in the schema of the UWB link, Figure 8. Also, two signal generators are there, viz. in the transmitter and as reference signal template in the correlation receiver. Both the generators can be implemented through the low-bit direct digital synthesis (DDS) discussed above. However, the receiver in Figure 9 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 9a.

Comparing the input and output signals for the correlation receiver, Figure 9, proves this statement qualitatively. Moreover, simulated for the case of the white Gaussian noise channel model shows that the processing gain is about of a small fraction of dB that is not worth for practice at all. Note here is no disagreement with the fundamentals of optimal reception for signal and noise additive mixture. In fact, the communication channel formed by two antennas with introduced pulse shaping exhibits the correlation processing. As such, the receiver can include only a sampling circuitry to catch the maximum of pulses at the receiver load. Of course, the system requires a quiet good performing synchronization that is required for the canonical case with correlation receiver also.

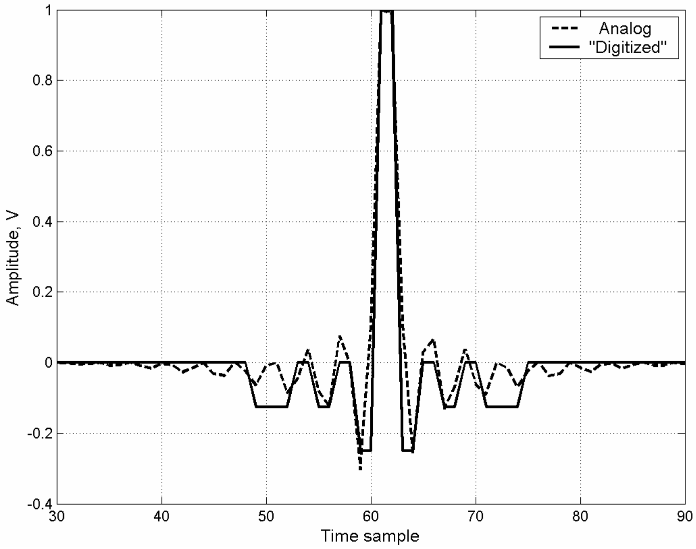


Figure 6. Digitizing of driving pulse for transmitting antenna as in Figure 3 with 3 bit amplitude resolution plus one sign bit and 150 ps sampling in time.

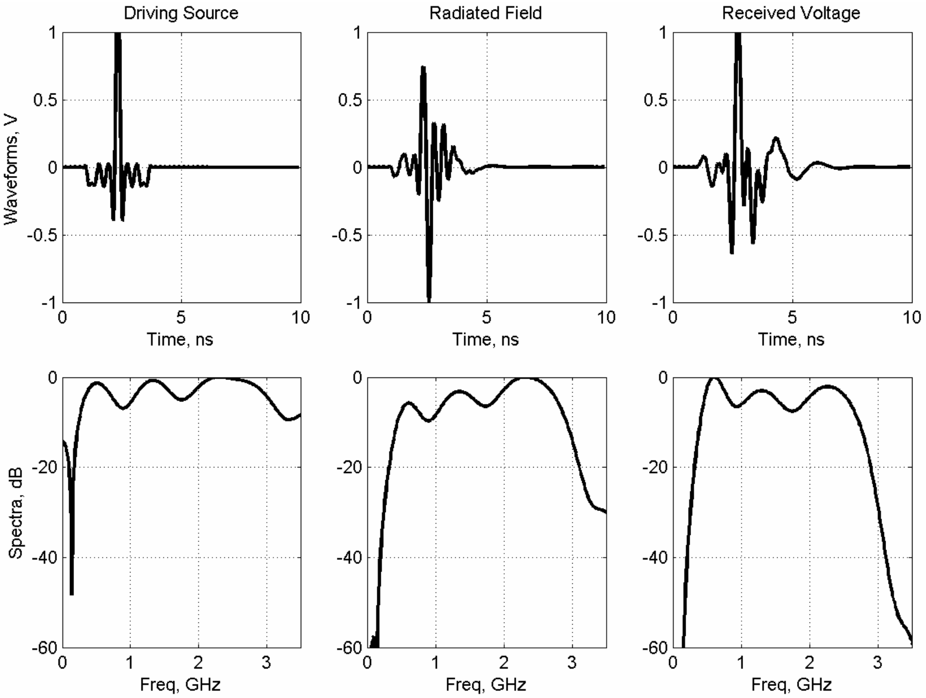


Figure 7. Pulse shaping through digitizing of driving pulse in accordance to Figure 7 in two-antenna UWB link with 15 cm long and 10 cm wide bow-tie dipoles. Total link efficiency is still about -30 dB.

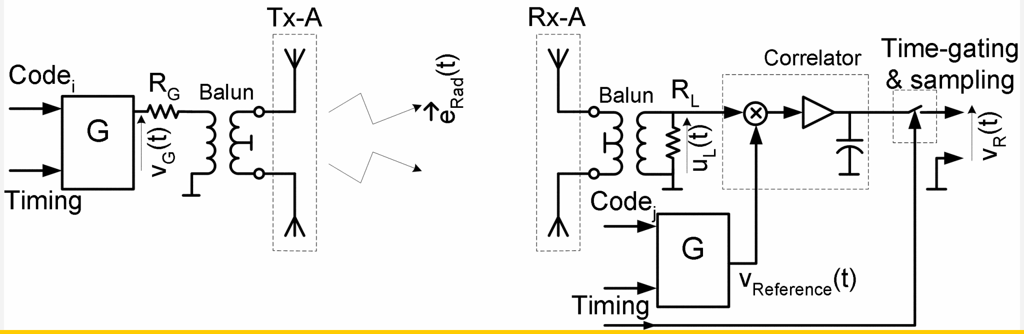


Figure 8. Complicated structure of UWB link comparing with simplified one in Figure 1a through introducing signal functional generator in transmitter and correlation receiver with signal template generator in receiver.

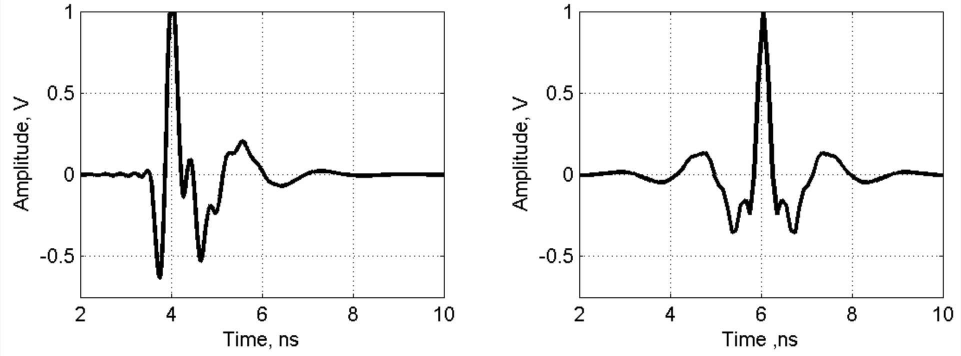


Figure 9. Received signal at the input (a) and output (b) of correlation receiver with pulse shaping through inversion of transfer function (1). Processing gain of correlation receive is negligible about 0.2 dB.

5. Conclusions

The proposed co-design of antenna and signals enables creating of signaling pulses with required features in time and frequency domain, high link budget, potentials 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 using of correlation receiver rather through the demonstrated pulse shaping. Furthermore, a combined numerical analysis is possible to simulate in time-domain both the electromagnetic part, viz. antennas, and nonlinear electronics of the transmitter and driving circuitry.

Also, complexity of real UWB links can be accounted accurately in analysis for complex geometries of real antennas, their packages and the whole multipart scenes including antennas' disturbance by nearby bodies. As well, blockage, multipath, through-wall propagation, antenna moving and other factors, which modify the UWB link features, can be predicted truthfully through the 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 including through-wall propagation and seeing, multipath and blockage mitigation, combining geolocation and wireless modes etc.

6. References

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