On the influence of antenna integration on the radio link of UWB systems for consumer equipment

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***Abstract*— The design of UWB systems for consumer electronic application requires the integration of the antenna for aesthetical design reason. This paper discusses the influence of the integration on the performance of UWB antennas and the entire radio link. Investigations based on numerical simulations show that the antenna performance is drastically affected when the antenna is integrated into the chassis of an application when classical UWB antenna measures like radiation pattern, ringing or delay spread are observed. In order to investigated the impact of this degradation on the radio link between different applications like DVD player and PDA in a typical living room environment propagation modeling is performed. The research shows that the less ideal classical antenna measures have only minor influence on the entire link compared to the influence of the indoor channel.**

***Index Terms*—UWB, antennas, delay spread, FDTD, transfer function, consumer equipment, propagation modeling.**

I. Introduction

The use of Ultra WideBand (UWB) systems, e.g. for wireless multimedia data communication between different home entertainment systems (DVD player, flat screen, Internet PC, …) becomes very appealing since the FCC released the spectrum from 3.1 GHz to 10.6 GHz for unlicensed low-power use [1]. It is the idea of mayor companies working in the definition and the design of consumer applications to unwire any wired connection, even the high data rate video links. Such a concept could be called *wireless* USB (Universal Serial Bus) similar to the well established *wired* USB interconnections. An interesting prospective on systems and applications is given in [2].

Especially for the design of systems entailing different antenna integration scenarios, it is essential to have fast and easy access to antenna characteristics by simple numerical simulations. This is important in the definition phase of a new product in order to predict the performance when prototypes are not yet available.

Meanwhile, there are many publications on suitable antenna concepts for such systems. However, most of them suffer from the fact that the antenna is investigated alone and the influence of the application in which the antenna will be integrated finally is neglected. This paper aims to investigate especially the influence of the antenna integration on the antenna performance in terms of classical antenna parameters matching, radiation pattern and delay spread on the one hand and the impact of these measures on the entire ink on the other hand.

In section II the methods applied are discussed briefly. This includes the antenna characterization by their spatio temporal transfer function as well as the definitions of classical UWB antenna measures. The methodology of the numerical simulations that apply the FDTD technique for the antennas and the ray-tracing techniques for the propagation is discusses. Section III investigates the influence of the integration on the antenna. The results for an classical bicone antenna in free space are compared to an antenna integrated into a DVD player and an antenna integrated into a PDA. In section IV the entire propagation link between different applications in a typical living room environment is modeled in order to investigate the influence of the antenna integration on the link performance.

II. Methods

A. *UWB antenna characterisation by spatio-temporal transfer functions*

From a signal processing point of view the antenna can be considered an LTI (Linear Time-Invariant) system which can be fully characterized by its transfer function [3]. The *transmit transfer function* $\boldsymbol{H}_{\mathrm{TX}}$ relates the radiated field at a certain location in the far field to the driving voltage at the antenna port. The *receive transfer function* $\boldsymbol{H}_{\mathrm{RX}}$ relates the received voltage at the antenna port to the incident plane wave at the antenna. Both, transmit and receive transfer function are related to each other by Lorentz’ reciprocity theorem. An expression that takes into account the ultra wideband properties of the system is:

$$2j\omega\mathbf{H}_{RX}\left(-\hat{\mathbf{k}},\omega\right)=c_0\mathbf{H}_{TX}\left(\hat{\mathbf{k}},\omega\right) \quad (1)$$

A detailed description of the formalism is presented in [3].

The above defined transfer functions provide a complete characterisation of the far field properties of the antenna. They can be used to treat the antenna as a module in system simulations or be used as the basis to calculate any other useful antenna measure.

B. Classical UWB antenna measures

For ultra wideband antennas specialized measures have been derived. Some of them, discussed in the following subsection are also reported similar in related literature, e. g. [4].

1) Group Delay:

As defined above the transfer function of an antenna is a complex measure and can be written in the following form

$$\mathbf{H}_{\mathrm{TX}}(\omega)=|\,\mathbf{H}_{\mathrm{TX}}(\omega)\,|\,e^{j\varphi(\omega)}\,. \quad (2)$$

The transfer function describes how a signals amplitude and phase is distorted by the antenna. A standard measure in filter theory is the group delay

$$\tau_g(\omega)=-\frac{d\varphi(\omega)}{d\omega} \quad (3)$$

which is defined as the negative derivative of the transfer functions phase. The group delay gives the average time delay the input signal suffers at each frequency, thus is related to the dispersive nature of the antenna.

In order to investigate the distorting effects a relative group delay can be defined:

$$\tau_{g,rel}(\omega)=\tau_g(\omega)-\tau_{g,mean}(\omega)\ . \quad (4)$$

Finally the standard derivative of the relative group delay provides a single number that characterises the dispersive behaviour:

$$\tau_{g,RMS}=\sqrt{\frac{1}{\omega_2-\omega_1}\int_{\omega_1}^{\omega_2}\tau_{g,rel}^2(\omega)d\omega}\ . \quad (5)$$

2) Impulse Response:

By inverse Fourier transformation of the transfer function of the antenna the impulse response can be calculated. For simplicity we use the equivalent baseband signal in this work. Furthermore, due to the fact that we calculated a limited frequency spectrum, we observe a truncation error if we apply the inverse Fourier transform directly. Therefore we multiply the frequency domain transfer function with a standard window function (Kaiser window) first before applying the inverse Fourier transformation. Detailed formulations are given in [4].

3) Ringing and delay spread:

A plot of the impulse response shows the ringing of the antenna which is a quite intuitive measure. The ringing indicates an impulse is spread by the antenna. A measure for the delay spread is derived from the impulse response as follows:

$$\tau_{DS}(\Phi,\Theta)=\sqrt{\frac{\int_{-\infty}^{\infty}(t-\tau_{DS,mean}(\Phi,\Theta))^2\ |\mathbf{h}_{\mathrm{TX}}\ (\mathrm{t},\Phi,\Theta)\,|^2\ dt}{\int_{-\infty}^{\infty}|\mathbf{h}_{\mathrm{TX}}\ (\mathrm{t},\Phi,\Theta)\,|^2\ dt}} \quad (6)$$

with

$$\tau_{DS,mean}(\Phi,\Theta)=\frac{\int_{-\infty}^{\infty}t\ |\mathrm{h}_{\mathrm{n}}\ (\mathrm{t},\Phi,\Theta)\,|^2\ dt}{\int_{-\infty}^{\infty}|\mathrm{h}_{\mathrm{n}}\ (\mathrm{t},\Phi,\Theta)\,|^2\ dt}\,. \quad (7)$$

C. Numerical Simulations

The antennas are investigated in their specific integration situation in the application by FDTD (Finite Difference Time Domain) modeling using the commercial available FDTD simulator EMPIRE™. For ultra wideband antennas a time domain simulation technique offers the advantage that the whole frequency spectrum can be calculated efficiently in a single simulation run. As the FDTD modeling covers only the near field problem, the far field is expanded from the near field data. The transmit transfer function is then calculated by relating the far field to the driving voltage at the feed point. The receive transfer function is calculated from the transmit transfer function by equation (1).

Thus the antenna is characterised completely by the spatio temporal transfer functions. The classical antenna measures are calculated from the transfer functions using the equation in section IIa. In order to investigate the radio link between different UWB applications the channel of a typical indoor scenario is characterized by propagation modeling using the ray tracing technique implemented in the commercial software *Wireless Insite*.

A detailed description of the numerical modeling is presented in [5].

III. Antenna Integration

UWB modules for the integration into consumer electronic products have to fulfill technical and non-technical requirements. The general technical requirement is that the module the has to be able to establish a link with the required data rate. Non-technical requirements are low prize, small size and the ability to be integrated into the device in order to prevent distortion of the aesthetical design. It is unlikely that a design driven product will use an external protruding antenna. For the antenna, especially the integration into the chassis of the application can be a serious problem, because it will interact with all components nearby. The performance parameters of the antenna like matching, radiation pattern and ringing will be affected by the specific integration. Moreover it will be necessary to adapt and tune the antenna to a certain integration scenario in a specific application.

It is obvious that all antenna parameters are affected when the antenna is transferred from the ground plane to a specific situation inside a (partly) metal chassis of an application like a DVD player or a PDA. However, in most publications this is neglected and the antenna characterisation takes only the antenna element into account and suppresses the integration.

A. *Bicone antenna*

In the first step just an bicone antenna is investigated as reference example. The bicone antenna is a classical UWB antenna. As a broadband dipole it provides an omni directional radiation pattern that shows moderate frequency dependency in the observed frequency range. The antenna used in this paper is described in detail in [3].

The impulse response of the bicone antenna is calculated from the frequency domain transmit transfer function of the antenna. Fig. 1 shows the transfer function for a single position. In order to achieve a smooth curve a Kaiser window has been used in addition.

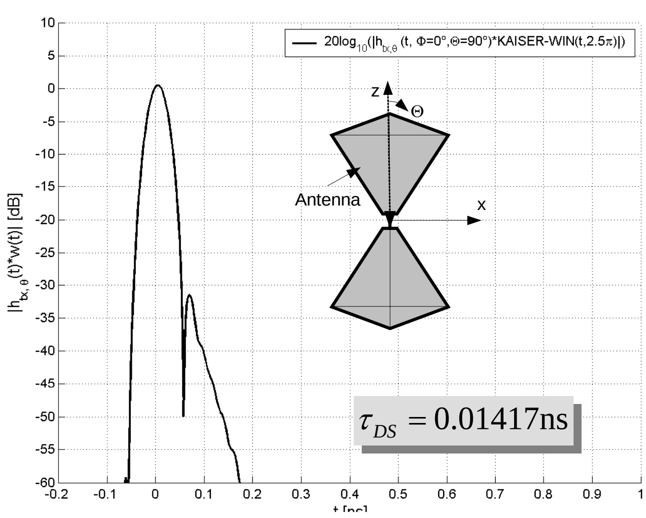

Fig. 1: Impulse response of the bicone antenna (Φ=0°, Θ=90°).

It can be noted from Fig. 1 that the ringing of the antenna is quite small. The delay spread is calculated to be:

$$\tau_{DS}(\Phi = 0, \Theta = 90°) = 0.01417 \text{ ns}.$$

B. *Antenna integrated in DVD player*

A suitable antenna concept for the integration into a device is e. g. a planar monopole. This antenna concept is derived from the bicone antenna when we use a planar representation of one cone above a ground plane.

The antenna is integrated within a volume inside the front face of the DVD player.

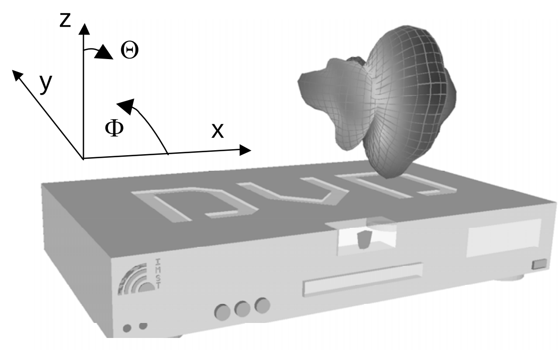

Fig. 2. Influence of the integration on the radiation pattern (e. g. at f = 7 GHz).

Fig. 2 shows clearly that the pattern depends very much on the specific integration scenario and is in any case no longer quasi omni-directional as it was mounted on the ground plane. Fig. 3 shows a horizontal plane of the radiation pattern of the model in as a function of frequency. It can be observed that the radiation pattern shows a strong frequency dependency. The system provides a single main beam up to 6 GHz, and side lobes occurring at higher frequencies. Furthermore, it is clearly illustrated that there are shadow areas located at the backside of the DVD player.

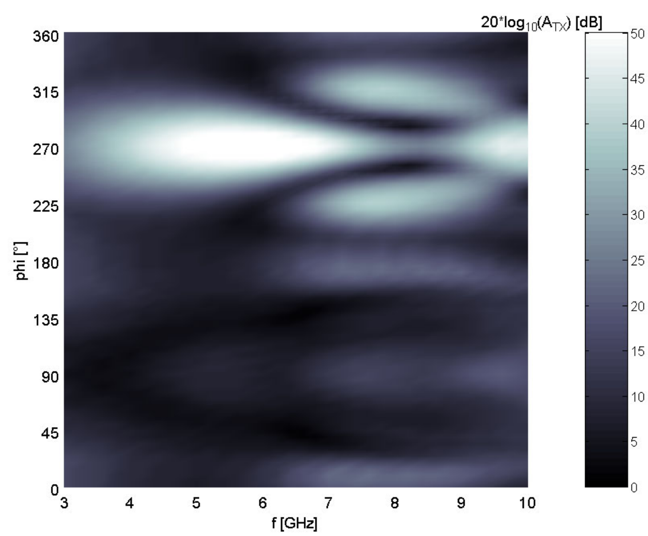

Fig. 3. Horizontal plane of the frequency dependent radiation patter of the scenario in Fig. 2 for $\Theta = 90°$.

In general we can conclude that even if the assumption of a metal chassis with only a small integration volume for the antenna may be quite pessimistic, it is clear that we cannot reach a quasi omni-directional radiation which is stable over the frequency range when the antenna is integrated in a realistic device. Therefore, the demand for omni directionality or frequency stability that is often requested is surely not feasible for low cost UWB antennas in consumer applications. However, at this stage it is an open question if we finally need such strict antenna demands to achieve sufficient network coverage in a home environment.

Fig. 4 shows that in addition the ringing becomes much longer compared to the bicone antenna in free space.

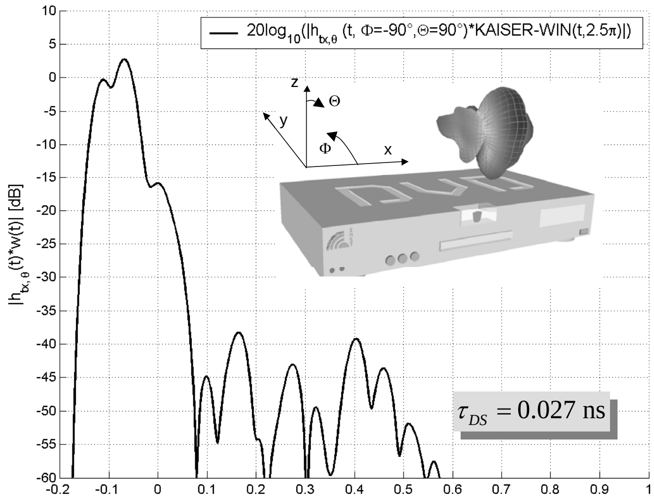

Fig. 4. Impulse response of the antenna integrated into the DVD player.

C. *Antenna integrated in mobile device (PDA)*

As a second realistic example the planar antenna is adapted to be integrated into a mobile device, such as a mobile phone or a PDA. In a mobile device space is even more limited than in a larger device like the above DVD player. If we consider e. g. a mobile phone it turns out that the integrated antenna is in close vicinity to other components and even has to share its volume with some of them. The model in Fig. 6 forecasts how it could look like for a mobile device with UWB antenna.

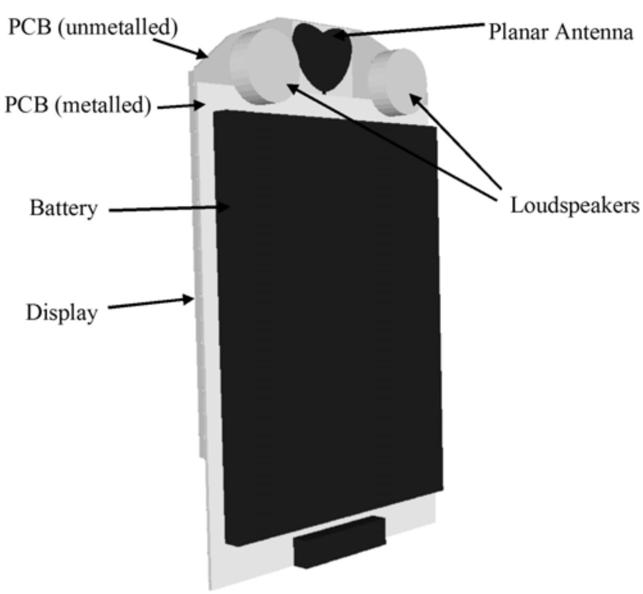

Fig. 5: Mobile device equipped with integrated planar UWB antenna.

The planar antenna element is located at top of the PCB (Printed Circuit Board). Other components, e. g. loudspeakers are located next to the antenna. The battery comes close to the antenna on the one side and the display partly overlaps on the other side. In order to apply the antenna concept we have to recess the metallization of the PCB under the antenna. Fig. 6 shows that it is possible to achieve a good broadband matching by this procedure.

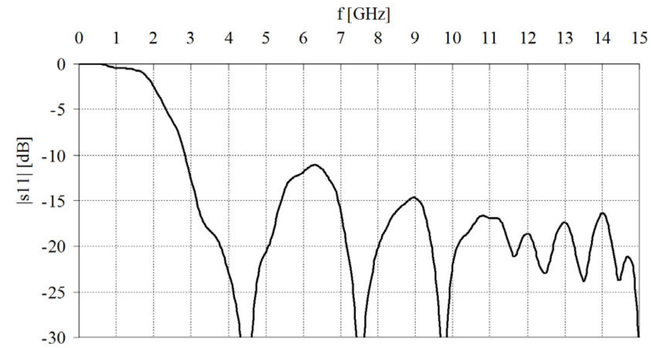

Fig. 6: Matching of mobile device equipped with integrated UWB antenna.

The transfer function is displayed for the Θ-component only, however due to the radiation from the edge of the PCB and the other components the antenna radiation contains also certain part of the Φ-component.

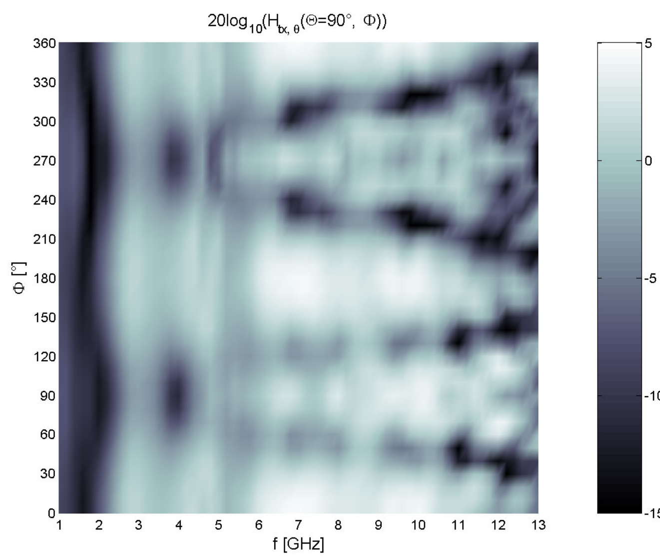

Fig. 7: Horizontal plane of the frequency dependent transmit transfer function of the mobile device with integrated UWB antenna.

Fig. 7a shows that the omni directionality holds only for the lower frequencies due to the planar antenna element on the one hand and the current distribution on the chassis of the mobile on the other hand.

It can be noted from Fig. 8 that the ringing of the antenna integrated into the mobile device is also significantly higher compared to the biconical antenna in free space. This is a result of the realistic integration situation of the antenna which leads to additional currents on the chassis and thus results in a much larger antenna which is composed out of the antenna element and the chassis of the mobile itself. The delay spread is calculated to be:

$$\tau_{DS}(\Phi = 90°, \Theta = 90°) = 0.0217 \text{ ns}$$

and is therefore also significantly higher compared to the biconical antenna in free space.

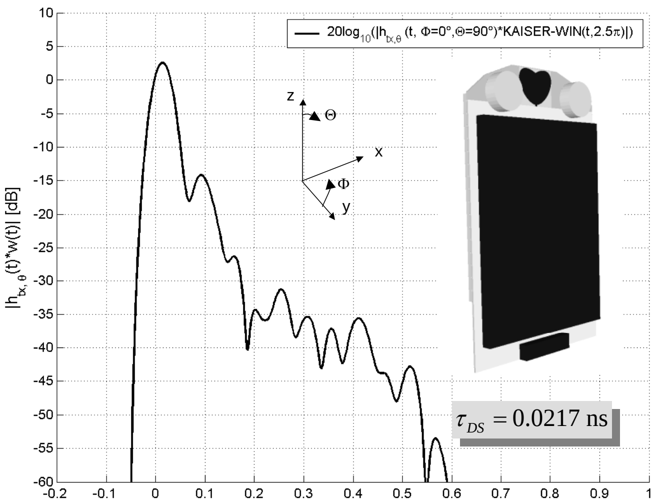

Fig. 8: Impulse response of the mobile device with integrated UWB antenna (Φ=90°, Θ=90°).

IV. Propagation Link Modeling

As mentioned earlier, depending on the system conception, network coverage by smooth power distribution may not be the only aspect. It might be also interesting to investigate how the signal will be distorted either by the antennas or the channel. In particular, because of the fact that the channel is given (living room environment), the designer can only affect (at least in principle) the distortion of the pulse by the choice the antenna [6].

In order to investigate the related aspects we make again use of the derived antenna characterizations including the specific integration scenario in combination with the ray-tracing model of the living room. As an example we can investigate the link between the DVD player (TX1) and the mobile device on the table (RX1) or any other combination shown in Fig. 9:

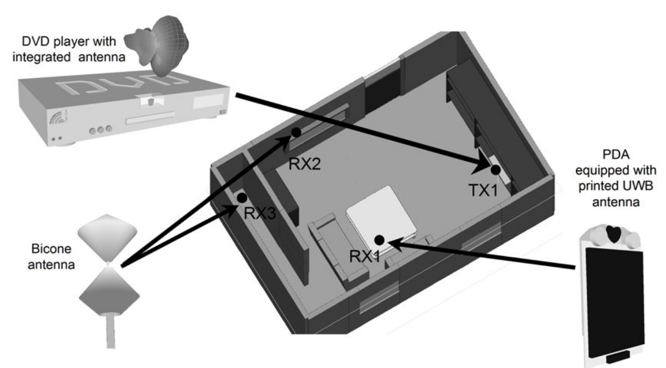

Fig. 9: Ray-Tracing model of a living room. The UWB module inside the DVD player acts as a transmitter (TX1). Other applications (PDA on table (RX1), flat screen on wall (RX2) modem in corridor) using different antennas are positioned at certain locations in the room and act as receivers for this example.

The entire link can be described in terms of the block diagram in Fig. 10. It includes the transmit transfer function of the transmit application, the transfer function of the channel and the receive transfer function of the receive application. Transmit and receive antenna transfer functions are taken from the FDTD modeling. The transfer function of the channel is calculated by the use of the ray-tracing software. In combination we result in a transfer function of the link system which results of the product of the single transfer functions in the frequency domain or the convolution in the time domain respectively. The notation chosen in Fig. 10 indicates that the transfer function of the link can also be interpreted in terms of scattering parameters which is a familiar measure to rf engineers.

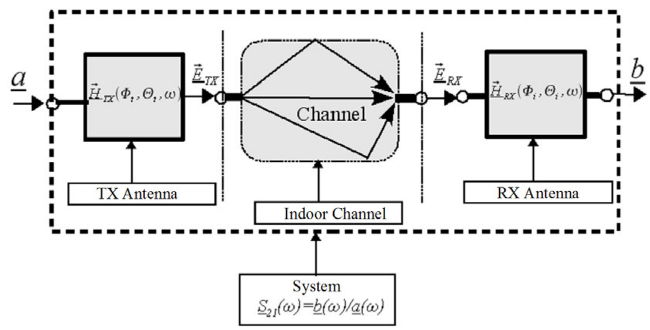

Fig. 10: Block diagram of the entire system including the antennas integrated in the applications and the indoor channel.

Fig. 11 shows the transfer function of the channel from the link between TX1 and RX1. It can be observed that the exponential decrease in frequency is superimposed by the effect of the multipath propagation in this indoor environment.

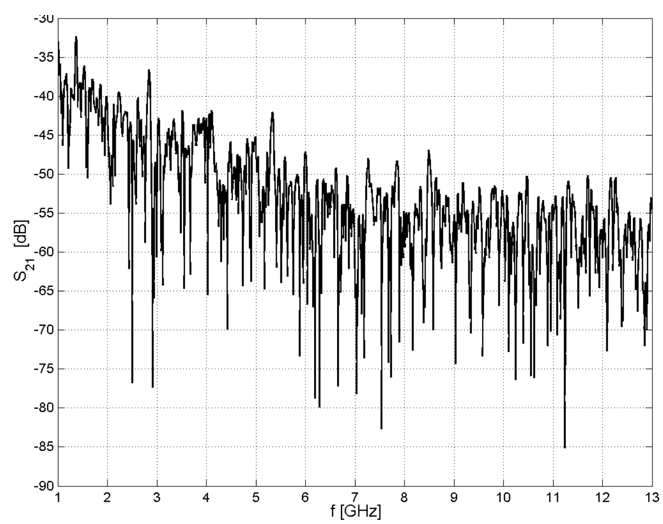

Fig. 11: Transfer function of the channel between TX1 and RX1 in the living room using ideal isotropic radiators.

By including the transfer functions of the transmit and the receive application we are able to calculate the impulse response of the entire link including realistic antenna integration scenarios by means of the inverse Fourier transform. In order to cope with the truncation of the spectrum we make again use of a window function in addition. Fig. 12 shows the impulse response of the link between the DVD player (TX1) in the shelf and the mobile device and the mobile device on the table (RX1) according to Fig. 9:

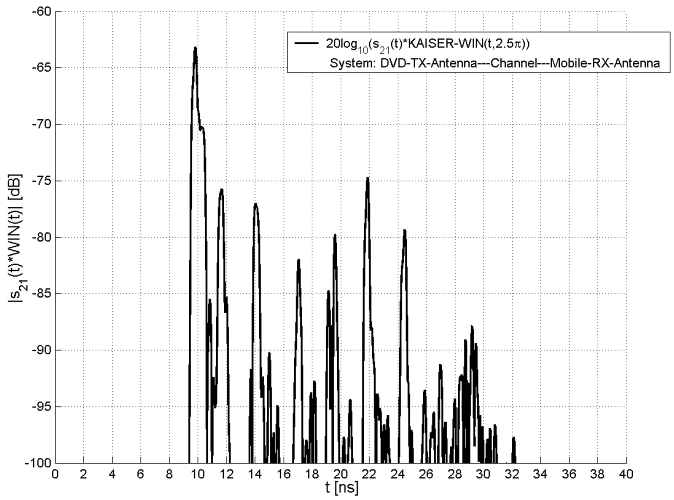

Fig. 12: Impulse response of the link TX1(DVD)-Channel-RX1(Mobile) taking into account the realistic antenna integration.

It can be observed from the impulse response in Fig. 12 that due to the LOS (line of sight) channel between TX1 and RX1 the first part of the signal arrives after 10 ns corresponding to a direct distance of 3 meters. The direct signal is followed by a number of reflections that are smaller in amplitude and are delayed according to the distance the traveled. All in all the impulse excited in the transmit system is spread over a significant time [6].

If we replace the antenna transfer functions of the realistic integration scenarios (antennas integrated into DVD player of mobile device) by the transfer functions of just biconical antennas in free space, we are able to compare the above result to a *quasi ideal* case with respect of the antenna. With this regard Fig. 13 shows the impuls resonse of link TX1(Bicone)-Channel-RX1(Bicone) neglecting realistic antenna integration. It can be observed that the overall spread of the signal for the *ideal* antennas is in the same order than for the case of the realistic *unideal* antenna integration. This is mainly due to the fact that the ringing imposed by the channel is significantly longer than the ringing of the antennas when they are integrated into the chassis of the application. Moreover, with respect to the specific link investigated there are even more echoes when the omni directional bicone antennas are used compared to the directive chassis integration.

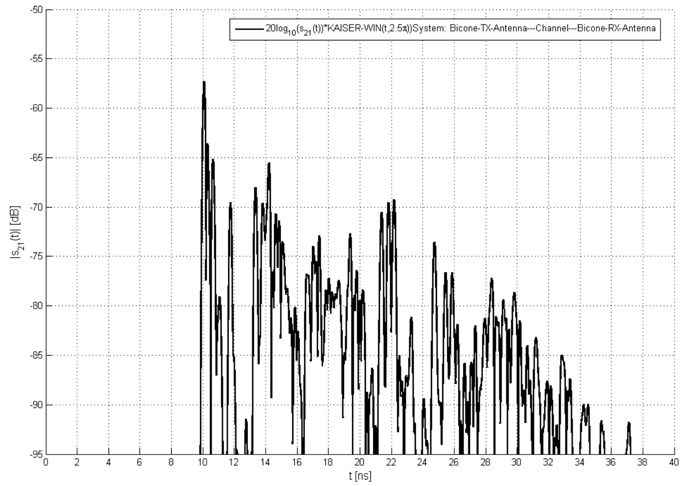

Fig. 13: Impulse response of the link TX1(Bicone)-Channel-RX1(Bicone) neglecting the realistic antenna integration.

V. CONCLUSION

The integration of small UWB antennas into the chassis of consumer electronic applications significantly affects the antenna performance. This leads to an degradation of the antenna performance if classical UWB antenna measures like frequency independent radiation pattern or ringing are observed. A realistic indoor UWB channel contains a remarkable amount of multi-path that leads to numerous reflections of the transmitted signal. The delay spread of the channel is much higher than the delay spread of the antennas, even if realistic integration is considered. Therefore the additional ringing due to the integration plays only a minor role for the overall link performance.

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