Imaging of the propagation environment by UWB channel sounding

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INTRODUCTION

The application of real-time broadband sounder systems for estimating the multidimensional geometric parameters of multipath wave propagation and its application to performance evaluation of MIMO (multiple input multiple output) transmission systems is already well understood. A channel sounder is used to record a sequence of MIMO channel impulse responses (CIR). During an off-line analysis session, the geometrical parameters of a ray-optical propagation model are estimated from the recoded data and used to deduce statistical channel models for radio link performance evaluation [1].
In this paper we will describe novel fields of application for real-time ultra wideband (UWB) sounder systems. At first we demonstrate precise real-time localizing of the transmit antenna. This application uses a SIMO (single input multiple output) setup and relies on the time-of-flight (TOF) estimation which takes advantage of the excellent range resolution of UWB signals. We also describe principles of UWB imaging that rely on SISO (single input single output) measurements. Those algorithms take the necessary spatial information from the motion of only one transmit antenna. If this antenna is moved along some suitable trajectory, it illuminates the propagation environment from different positions. Then the recorded CIR provides enough information for the geometrical reconstruction of the actual propagation environment in terms of location, shape, and size of the scattering objects.

ESTIMATION OF ANTENNA POSITION

The UWB channel sounding setup usually comprises a receiving antenna array which plays the role of the stationary access point (AP) and a moving transmit antenna which emulates the UWB terminal. The responses of the AP antennas are precisely calibrated in terms of the transmitted UWB signal TOF. Their resulting positions in the local coordinate system are assumed to be a priory known. Therefore, the AP antennas can be used as an array of distributed reference beacons for active terminal localization. This localization approach takes advantage of huge bandwidth of UWB signals. As it is based on wideband TOF estimation and triangulation, the optimum reference antenna positions should span a wide base line. There is no range ambiguity involved as long as the repetition rate of the signal is adequately chosen.
The terminal antenna coordinates relative to the fixed infrastructure antennas are calculated from the line of sight (LOS) components of the CIR sequence. For the time being, let us assume a 2 element receive antenna array and a mobile station comprising one omnidirectional transmit antenna (see Fig. 1). The calibrated AP antenna positions define the origin of the local coordinate system. The TOF of the LOS waves from the Tx antenna to any receive antenna is estimated by correlation of the received wave with respect of the reference response. The possible Tx antenna position determines the radius of a circle around the respective reference antenna location (see Fig. 1). The position of the transmit antenna is determined as an intersection of two circles:

$$\left(x(t)+\frac{D}{2}\right)^2+y(t)^2=s_1(t)^2 \qquad \text{and} \qquad \left(x(t)-\frac{D}{2}\right)^2+y(t)^2=s_2(t)^2 \tag{1}$$

whereby $s_1(t)$ ($s_2(t)$) is the TOF between Tx and Rx1 (Rx2) multiplied by the velocity of light. The Cartesian coordinates [$x(t),y(t)$] of the transmit antenna are obtained by solving equations (1) analytically. There still remains a geometric ambiguity which can be eliminated by exploiting a priory knowledge about the terminal position or by using an additional receive antenna element. For 3D estimation we need at least 4 antennas which should be arranged as a tetrahedron of maximum volume. Perfect Rx/Tx timing synchronization, as it is required for one ways TOF estimation, however maybe a problem if there is no wired Tx/Rx synchronization available. In this case we need a further reference antenna as it is known, e.g., from GPS.

UWB IMAGING

Imaging performed by electromagnetic waves is well known from non-destructive testing, ground penetrating radar, through-wall radar, medical diagnosis, etc. These methods exploit the scattering of electromagnetic waves in an unknown medium and involve some form of back propagation, back projection, or time-reversal for image reconstruction. Time domain imaging methods using broadband or UWB excitation signals are usually referred to as migration [2]. A well-known method is the Kirchhoff migration which uses a ray optical model of wave propagation and assumes Rayleigh or specular scattering of waves from objects. This requires the size of the objects to be clearly smaller or larger than the wavelength of the excitation signal. Note that in case of baseband UWB signaling, the relative span of wavelengths involved is very wide. If the object size is in the order of any wavelength involved, this gives rise to structural resonances or geometric induced dispersions of waveforms which causes image blurring. Moreover, Kirchhoff migration assumes a constant wave velocity, which must be a priory known. Despite of these limitations, Kirchhoff migration is widely used due to its relatively low computational complexity compared to other imaging methods.
Kirchhoff migration is illustrated in Fig. 2. It consists of a 2D bistatic measurement comprising one fixed receiver and a moving transmitter which excites the propagation channel by an UWB wave. The transmitter moves along a line and illuminates objects from different positions (Tx1, Tx2, …). The captured CIR sequence is represented as a 2D data structure, in which the vertical dimension (representing the instantaneous CIR) is related to the round-trip time delay and the horizontal dimension refers to the instantaneous position of the transmitter. If we assume for example only one single point scatterer within the whole scenario, than the peak of the scattered electromagnetic waves appears as a hyperbolic trace in measured data (see Fig.2 bottom). The Kirchhoff migration maps the samples of each backscattered response to an ellipse in the migrated image (only sections of the ellipses are shown in the figure). The migrated images of all captured records are superimposed. The contribution of any point scatterer adds coherently up at its true position. In this way, a focused image is generated. The migration process is described by:

$$o(x,y) = \frac{1}{N}\sum_{n=1}^{N} R_n\left(\frac{r_{RX}+r_{TXn}}{v}\right), \tag{2}$$

whereby R_n is the measured CIR at the transmitter position TX_n. Since the measurement system works in the base band, R_n is real valued. r_{RX} is the distance between the receiver and the assumed scattering object located at (x,y). r_{TXn} is the distance between the transmitter and this object, v stands for the propagation velocity and $o(x,y)$ represents the migrated image. The quantity $(r_{RX}+r_{TXn})/v$ is the round trip time delay of the electromagnetic wave propagating from the transmitter to the assumed object and back to the receiver.

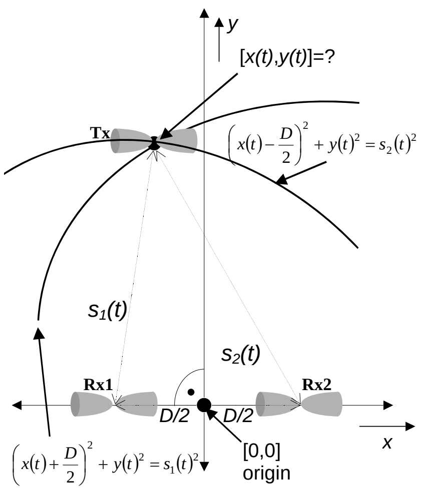

Fig. 1 Estimation of antenna positions

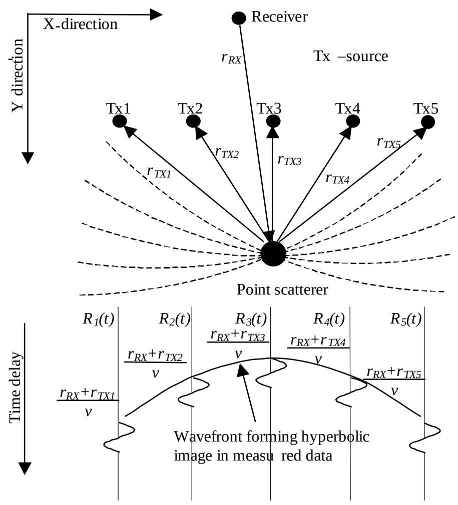

Fig. 2 Kirchhoff migration

In channel sounding application, we can apply Kirchhoff migration to generate focused images of the propagation environment. This gives us much more information about the geometrical structure of the propagation environment than traditional sounding techniques. Obviously, a SISO measurement setup is sufficient to generate focussed images as long as one antenna is moving. The antenna track spans a synthetic aperture and, thus, provides information about the object spatial distribution. We have to make sure that the measured CIR sequences contains sufficient back scattered information from the objects of the environment by illuminating it from different positions and we must precisely know the positions of the antennas involved (including position estimates of the moving antenna).

MEASUREMENT EXAMPLES

An experimental MIMO (3 Tx / 4 Rx) UWB sounding system covering the band from near DC to 4.5 GHz was used for the measurement examples described below. It is a 9 GHz clock rate base band version of the system described in the accompanying paper [3]. The accuracy of the antenna position estimates is of major importance. It depends on the arrangement of the reference antenna elements, the measurement system performance (jitter and noise) and on the antenna calibration. The latter is related to the precise knowledge of the temporal antenna radiation characteristics. The following example demonstrates the achieved precision of the 2D position estimation of a moving antenna. A Rx antenna array consisting of 3 collocated Vivaldi antennas was used as reference. These antennas were arranged in the horizontal plane as a triangle (equal-sided, antenna distance 0.5m). The transmit biconical antenna was mounted on a 2D positioning unit which allows the positioning of objects with 0.75 mm precision in two directions. The transmit antenna was moved along a predefined track (see Fig. 5). The data were recorded by the UWB system. Fig. 3 shows the results of 3 different estimation algorithms together we the true track of the transmit antenna. The first algorithm had no knowledge about antenna characteristics and performed no interpolation of measured channel impulse responses. The second one improved the results by interpolation and the third algorithm took into account also antenna characteristics gained by the calibration measurement. The improvement of the position estimation is clearly visible in the detailed view in Fig. 4. The third algorithm has a standard deviation of the range estimation in an order of 3mm and the standard deviation of the azimuth in an order of 0.75 degree. More detailed description of the algorithms can be found in [4].

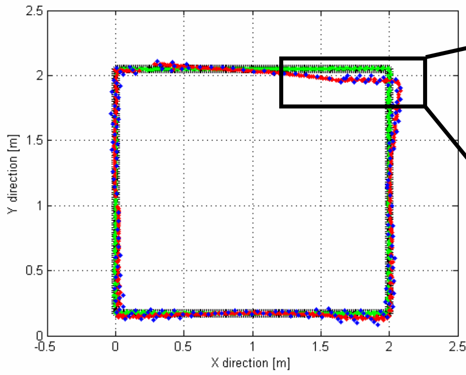

Fig. 3 Estimated positions of moving transmit antenna

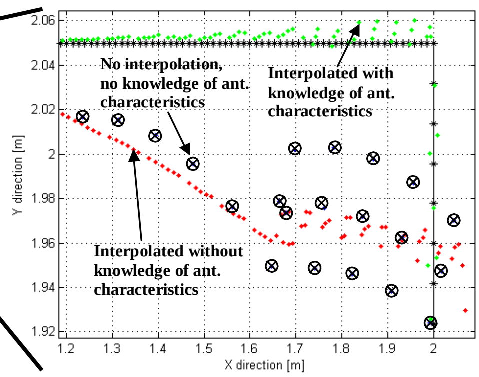

Fig. 4 Detailed view

The second measurement experiment demonstrates application of the sounder for UWB imaging. Here, the same measurement arrangement was used as in the previous measurement example. The measurement scenario is depicted in Fig. 5. Measured data of one receive antenna (1000 impulse responses) are illustrated in Fig. 6. Here, the direct wave is clearly visible. This direct wave at the 3 Rx antennas were used for the localization of the moving transmit antenna. Multipath components were extracted from the measured data by signal preprocessing (see Fig. 7). They provide information about the propagation environment. This part of the data is focused by the Kirchhoff migration. The result is illustrated in Fig. 8. The walls of the measurement lab can be clearly identified from the UWB image.

OUTLOOK AND CONCLUSIONS

We have demonstrated the application of radar imaging methods to generate an object distribution map of the propagation environment from real-time UWB sounding data. The procedure takes the necessary spatial information from the motion of only one antenna. The required precise position of the moving antenna is estimated by using a distributed Rx antenna array and TOF measurement. We have presented a very first measurement example. The image quality can be still considerably improved using more sophisticated imaging techniques and better antenna arrangement. The result depends also on the track shape for the transmit antenna. The proposed measurement procedure offers interesting far-reaching perspectives summarized as:

- *High-resolution, 3D-characterization of the multipath propagation.* UWB imaging of the propagation environ ment helps to better understand the propagation phenomena and to deduce geometric channel models [5].
- *Imaging of static and moving objects.* The demonstrated example is restricted to the imaging of stationary parts of the environment. The procedure can be extended to separate between stationary and moving objects. This requires an additional transmit antenna, which is kept stationary throughout the measurement procedure.

- *High-resolution, 3D active localization.* The example shows the potential localization performance of UWB terminals. Since the terminal actively transmits (or receives) a UWB signal and since, in general, there is a cooperative interaction of the terminal and the infrastructure, we call this "active localization" [6].
- *Joint active and passive localization.* The example demonstrates that an UWB terminal can gain considerable information about the geometric and electromagnetic structure of the propagation environment if it is moving. One application example is the detection of unexpected (perhaps time varying) obstacles by a moving robot.
- *Cooperative, distributed sensor networks.* Distributed ad-hoc sensor networks are discussed as one promising application scenario of UWB technology. The superior localization ability of UWB sensor nodes can be exploited to support the network organization. Vice versa, cooperation of sensor nodes can considerably enhance the localization, imaging and object detection ability.

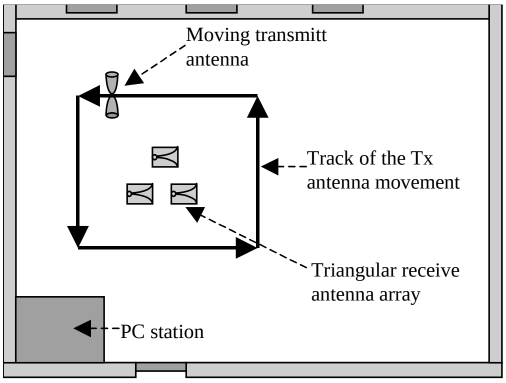

Fig. 5 Measurement scenario

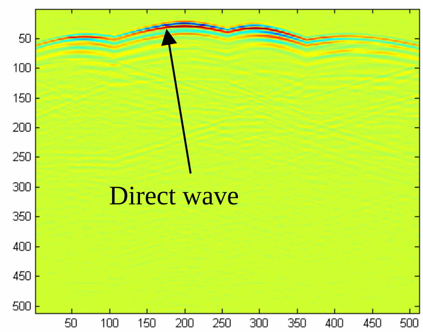

Fig. 6 Measured data

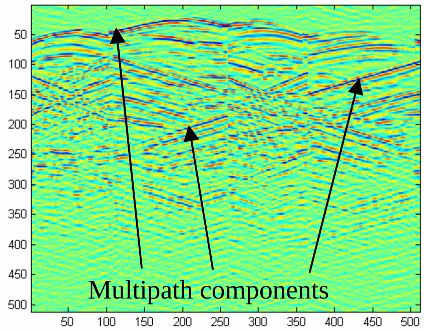

Fig. 7 Preprocessed data

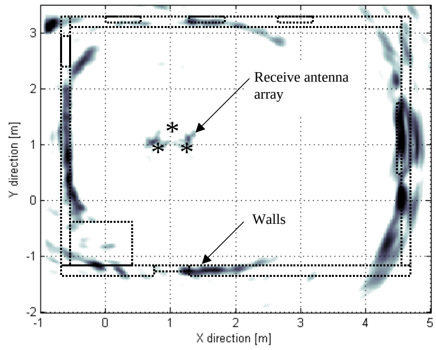

Fig. 8 UWB image of the propagation environment

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