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DISTRIBUTED UWB MIMO SOUNDING FOR EVALUATION OF COOPERATIVE LOCALIZATION PRINCIPLES IN SENSOR NETWORKS

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ABSTRACT

We describe architecture, design, and a novel application of a real-time MIMO UWB channel sounder. The sounder is applied for evaluating of localization principles in distributed sensor networks that are based on UWB radio technology. We assume an application scenario without any supporting infrastructure as it may occur in emergency situations such as fire disasters, earthquakes or terror attacks. At first we discuss the deployment scenario and signal processing principles applied for cooperative sensor node localization and imaging of the propagation environment. Then, we describe the architecture of the UWB MIMO channel sounder. Finally, a measurement example is demonstrated.

1. INTRODUCTION

MIMO channel sounder systems are usually applied for MIMO (multiple input multiple output) transmission link performance evaluation and for estimation of the multidimensional geometric parameters of multipath wave propagation [1]. Ultra wideband (UWB) propagation measurement, so far, was based on network analyzer application [2] which allows only static measurements. Here we describe a novel distributed real-time UWB MIMO sounder system and its application for evaluating cooperative localization principles in sensor networks. This deployment scenario is motivated by the use of sensor network to manage emergency situations. The sensor nodes should be able to navigate in an unknown or even hostile environment, identify hazardous situations such as sources of fire, locate buried-alive persons and roughly check the integrity of building constructions, etc. For this application, the fundamental advantage of UWB is the capability to penetrate objects and dusty air by simultaneously delivering high-resolution information about the position of the objects in the environment, their internal structure as well as material composition.

The sensor network consists of a number of mobile or deployable sensors equipped with one UWB transmitter (Tx) and/or receiver (Rx) antenna. We will refer to them as “sensor nodes”. These nodes are autonomously operating in an unknown indoor environment without any supporting infrastructure. They are cooperating to enhance their localization and object recognition performance. Under these assumptions, sensor networks have to:

- establish a network of “anchor” nodes to act as reference for localization of manoeuvrable nodes,
- recognise the geometric structure of the environment and relate it to the sensor network coordinate system,
- detect and identify unknown obstacles,
- recognise static and moving objects,
- find human beings and check their vital functions, etc.

We describe distributed and cooperative signal processing techniques for localisation of sensor nodes within an environment. In contrast to previous research [3], [6], [7] we assume that neither any supporting infrastructure is available, such as reference beacons, nor a priori information from maps or floor plans. Therefore, the geometric structure of the environment has to be recognised and related to the sensor network coordinate system. Supposing that the unknown propagation environment is properly illuminated by some Tx nodes, its geometric structure (in terms of location, shape, and size of the scattering objects) is reconstructed from the data recorded by one or more roaming sensor nodes.

Signal processing principles applied in sensor networks for sensor node localization and imaging of the propagation environment will be demonstrated based on real-time UWB measurements. These measurements were performed by the distributed real-time UWB MIMO channel sounder to be described in this article.

2. LOCALIZATION OF SENSOR NODES

To recognize the geometrical structure of an environment it has to be explored by a number of mobile sensor nodes roaming about on arbitrary tracks. The environment is illuminated by one or more Tx nodes. Rx nodes record the backscattered waves. Images of the environment are created by fusing the recorded data from different Rx nodes. The knowledge of the precise location of each sensor node is prerequisite for the implementation of an imaging algorithm. Since there is no reference beacon infrastructure available, the nodes must at first put up their own local coordinate system by estimating their relative position. This finally allows implementing of imaging algorithms, recognizing the structure of the environment, and relating it to the network coordinate system. E.g., the first two sensor nodes entering the environment take the following actions:

- estimate the range between the sensor nodes,
- estimate the range between each sensor node and other objects.

This information allows sensor nodes to move through the environment without crashing to each other or against other objects and to optimize their position. After having found suitable positions, these two sensor nodes stop their movement and serve as anchor nodes for other roaming nodes. The anchor nodes create the basis of a coordinate system with its origin e.g. at the position of the first sensor node Tx1/Rx1 and the X-axis crossing the second sensor node Tx2/Rx2 as illustrated in Fig. 1. Thus, the first sensor node has coordinates [0,0] and the second one [d_{21},0], where d_{21} is the estimated distance between these two nodes. When the third sensor node Tx3/Rx3 enters the environment its 2D position is uniquely estimated relative to the already established coordinate system as far as it does not cross the X-axis. For the unique 2D position estimates of other roaming nodes 3 anchor nodes creating local coordinate system are necessary.

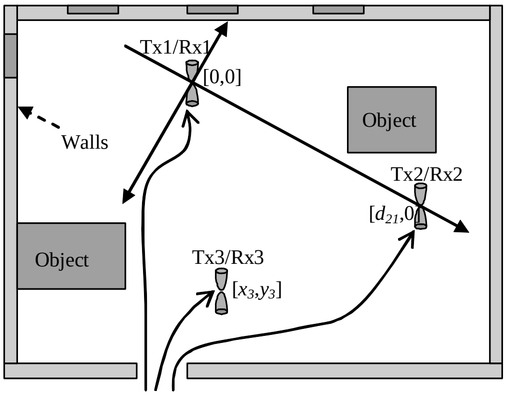

Figure 1 – Application scenario

In general, sensor node localization is performed in two steps. The goal of the first step is to measure and estimate some localization related signal parameters like time delay, angle, or amplitude of the arriving signal [3]. Here we will focus on time-of-arrival (ToA) based algorithms because of their superior resolution in case of UWB and since we consider nodes with only one Rx and/or Tx antenna. Furthermore, we assume line-of-sight (LOS) connection on the relevant links between the nodes. This seems reasonable since with enough redundancy in the number of anchor nodes, LOS links can be selected. Moreover, the node positions are supposed to be optimized to avoid non-line-of-sight (NLOS) links and, at the same time, span a wide base line for precise localization. The second step is data fusion which combines data from all available nodes for location estimation. These techniques depend on which signal parameter is estimated at a particular sensor node. For more information see the overview given in [3].

The basic principle of ToA based localization is illustrated in Fig. 2. ToA (also referred to as a time-of-flight) is related to the distance between the transmitter and the receiver. The estimated range defines a sphere (in the 3D case) of constant distance around the transmitter. The intersection of spheres resulting from multiple range measurements relative to several available Tx anchor nodes provides the location estimate of the mobile sensor node. Fig. 2 illustrates a 2D measurement constellation using the minimum number of two anchor nodes (Tx1 and Tx2). Tx1 and Tx2 provide range estimates r_1 and r_2 that describe the scenario by 2 quadratic equations delivering 2 solutions for the location estimation. One solution is the true position. The second one is an ambiguous solution, which can be eliminated by using an additional sensor node. Moreover, if more then the minimum number of sensors nodes is available, the over-determined system of equations can also be solved to achieve a MLSE position estimate [3].

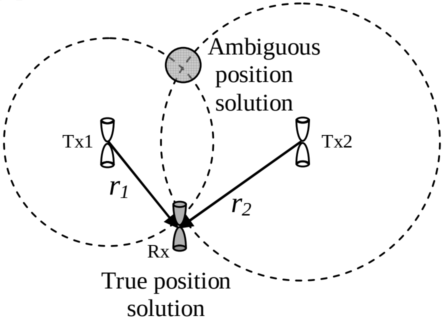

Figure 2 – Range based location estimation

3. IMAGING OF THE PROPAGATION ENVIRONMENT

Imaging performed by electromagnetic (EM) waves is well known from non-destructive testing, ground penetrating radar, through-wall radar, medical diagnosis, etc. These methods exploit the scattering of EM 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 [4]. 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. The principle of the Kirchhoff migration is illustrated in Fig. 3. Here, we assume a 2D measurement comprising one fixed receiver Rx and a moving transmitter Tx. The transmitter moves along a line and illuminates objects from different angles (positions Tx1, Tx2, …). The captured CIRs represent a 2D data structure, in which the vertical dimension is related to ToA and the horizontal dimension refers to the instantaneous position of the transmitter as illustrated in the bottom part of Fig. 3.

If we assume for example only one single point scatterer within the whole scenario, than the peak of the scattered EM waves appears as a hyperbolic trace in measured data (see Fig.3 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 CIRs 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:

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

whereby R_n is the measured CIR at the transmitter position Tx_n, 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 EM wave propagating from the transmitter to the assumed object and back to the receiver.

In channel sounding application for the evaluation of sensor networks, we 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 focused images as long as one antenna is moving. The antenna track spans a synthetic aperture and, thus, provides information about spatial information about the environment. We have to make sure that the measured CIRs contain sufficient back scattered information from 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.

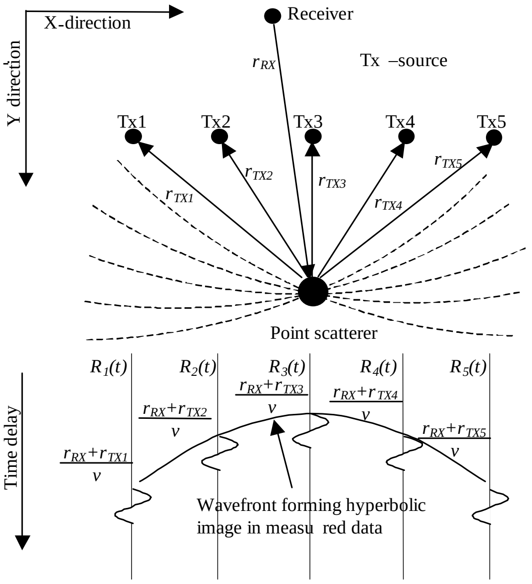

Figure 3 - Kirchhoff migration

4. REAL-TIME UWB MIMO CHANNEL SOUNDER ARCHITECTURE AND DESIGN

The channel sounder, used for the measurement experiments described in sect. 5, uses a binary sequence to sound the radio channel. From the realisation point of view this has clear advantage against alternative signals like chirp, stepped sine wave, or short pulse. For example, apart from its cost, the network analyzer (stepped sine wave signals) can easily meet the UWB bandwidth demand. However, real-time MIMO operation is prohibited by its slow measurement rate. Other concepts, e.g. short pulse systems, offer real-time operation but they are often subjected to a higher susceptibility to jitter and drift. On the other hand, binary sequences can be easily generated up to tenths of GHz of bandwidth by a digital shift register with a frame repetition rate up to millions of binary sequences per second. Binary sequences are transformed to short pulses by a cyclic correlation. Besides of the advantage of having a reasonable correlation gain, these stimulation signals are characterized by small binary voltage amplitudes that allow extremely fast digital switching in integrated circuit technology to meet the demanding requirements on bandwidth and low jitter.

Fig. 4 presents basic architecture of the channel sounder [5]. The sounder is controlled by a single tone clock. Digital shift register generates the stimulation signal -M-sequences. Since M-sequences are periodical and the measurement scenario can be assumed to be locally stationary, it is possible to acquire them by an under-sampling approach. Here, the binary divider (2^m) determines the sub-sampling factor and provides the receiver sampling clock. The measurement data are captured by a Track-and-Hold circuit (T&H), transformed into the digital domain (ADC), optionally synchronously averaged (p is number of averages) and finally online processed (DSP) or stored for off-line processing. The impulse response results from an impulse compression, which is performed by the FHT (Fast Hadamard-Transform) and is equivalent to the cyclic correlation. The FHT-algorithm is very close to the FFT-algorithm except that it is based on a pure summing of data samples, which offers very fast operation for special hardware implementation.

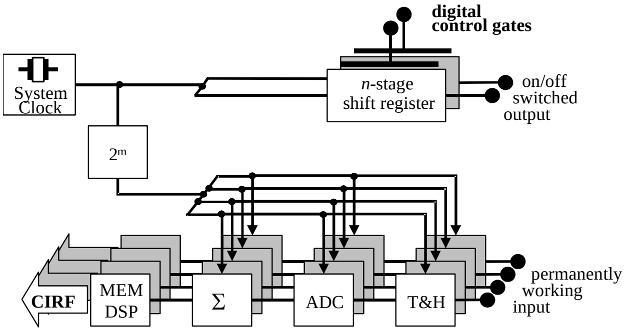

Figure 4 - Architecture of the real-time UWB MIMO channel sounder

Fig. 5 shows the multi-channel base band UWB sounder, which is build in a 19 inch rack. It has been designed at Ilmenau University of Technology in cooperation with MEODAT company in the frame of the EU project PULSERS. It was developed using SiGe monolithic integrated circuits (shift-register, binary divider and T&H). The extremely linear time axis and the superior jitter and drift behaviour, compared to traditional sequential sampling oscilloscopes, is the result of the synchronous digital controlled sub-sampling. The DSP module of the described experimental systems is based on standard off-shelf PCB products. The ADC is a 12-Bit-Video ADC and the sampling frequency is 13.7MHz.

The sounder has 2 transmitters and 4 receivers. It is driven by a 7GHz system clock what results in a bandwidth of 3.5GHz (baseband). The generated M-sequences are 585ns long. The measurement rate is up to 3300 sequences per second. The calibrated sounder offers dynamic range over 55dB. Currently, the sounder is working in the base-band, however, system extensions to cover other frequency bands like 3.1-10.6 GHz (given by the Federal Communications Commission mask), or 60GHz are planned in the near future and had been already successfully tested in the laboratory environment.

Figure 5 - Real-time UWB MIMO channel sounder design

5. MEASUREMENT EXAMPLES

The following measurement experiment will present application of the channel sounder described above for the evaluation of the discussed sensor network processing techniques. We will demonstrate the estimation of the sensor node location within a sensor network with minimum number of sensors and the imaging of the “unknown” environment which is inspected by these sensor nodes.

The measurement has been performed at the Institute for design theory and plastics processing machinery at University Duisburg-Essen. Fig. 6 gives an impression of the environment. The ground plan with some objects situated in the vicinity of the inspected area is shown in Fig. 7. Edges of metallic objects that are assumed to be detected are emphasized by bold lines. Anchor sensor nodes were represented by two receive antennas Rx1 and Rx2 situated 1.5m above the ground. These two anchor nodes define coordinate system with its origin at the position of Rx1 and the X-axis crossing the Rx2 sensor node. Thus, the location of Rx1 is [0m, 0m] and the location of Rx2 was [6.02m, 0m].

The first goal of this measurement demonstration was to estimate the location of the mobile transmitter Tx. The transmit antenna was moved during the measurement by a walking person (a real-time measurement). The track of the movement was chosen by the person carrying the antenna so that the area among objects of this environment is scanned dense enough to provide sufficient information for the imaging algorithm for the reconstruction of the geometrical structure of the environment.

Location estimation was performed by time-of arrival localisation techniques. The signal parameter ToA was estimated using a matched filter based estimator. Signal parameters estimated for both anchor nodes Rx1 and Rx2 were fused together by the range based data algorithm. The usage of only two anchor nodes was allowed by the following facts:

- we have assumed only 2D case,
- we have assured that the Tx motion is within the upper half-plane of the coordinate system, which removes the ambiguous position solution as illustrated in Fig.2,
- the channel sounder used for the measurements synchronises transmitters and receivers by a wired connection, so there was no need to use additional sensor node for the time offset estimation, or measurements of round-trip-times.

Since there was used minimum number of sensor nodes, the system of obtained equations was not overdetermined and was solved analytically. More details can be found in [8].

The result of the location estimation is shown in Fig. 8. For the better illustration there are only depicted each 16th Tx location estimations represented by asterisks. Altogether there were measured and estimated more than 4000 Tx locations during the Tx antenna movement. The precision of the location estimation is assumed to be in an order of about 5cm. This is worse than the results described in [8], where the precession was almost in an order of millimetres. The precession degradation was caused due to the free-hand Tx antenna movement. During the movement the Tx antenna was tilted by the carrying person and moreover its height has also deviated from the 1.5m height of the Rx antennas. This violated our first assumption of the 2D measurements.

The estimated locations of sensor nodes and CIRs measured by Rx1 and Rx2 were used for the reconstruction of the geometrical structure of the environment. The reconstruction was performed by the Kirchhoff migration algorithms described before. The migration was first applied to each anchor node (Rx1 and Rx2) separately and then the gained images were superimposed resulting in an intensity image as shown in Fig. 8. Here, black assigns a high reflectivity of an object i.e. the presence of strong scatter signals.

Figure 6 – Measurement environment

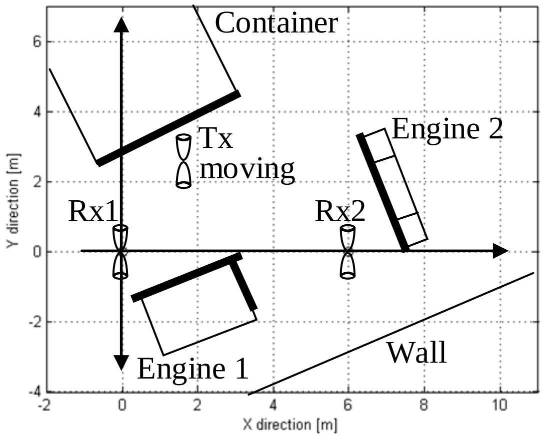

Figure 7 – Ground plan of the inspected environment

A pale grey reflects a presence of a weaker scatter. Clutter signals and minor reflections are excluded from the image by thresh holding. The clutter arises e.g. due to the multiple reflections among objects, or antenna-objects interactions, that were not taken into account by the applied focusing algorithm. The image clearly identifies the location of the fronts of the objects as indicated in Fig. 7. Edges give a pronounced reflex in the migrated image.

Note that the resulting amplitude (grey intensity) of the focused image is affected not only by the ability of objects to reflect EM waves, but also by the selected track of the roaming node(s) illuminating the environment. Therefore, it is necessary to select the track appropriately and to pay attention to strategies applied in the measurement and subsequent data fusion algorithms. This is a challenging task and will be researched in the near future.

6. CONCLUSIONS

We have discussed and demonstrated by a measurement example a new field of UWB channel sounder application. The sounder was applied for the evaluation of the localization principles in distributed sensor networks. We have shown cooperative localisation of distributed sensor nodes in an environment without any infrastructure. Furthermore, the reconstruction of the geometrical structure of this environment in terms of position and shape of static objects present within this environment was demonstrated. Similar techniques can be used to detect and localise moving objects. For the purpose of that, the sensor nodes stop their movement and observe moving objects. An example of it can be found in [9]. Here, the detection and localisation of people is demonstrated using measured data.

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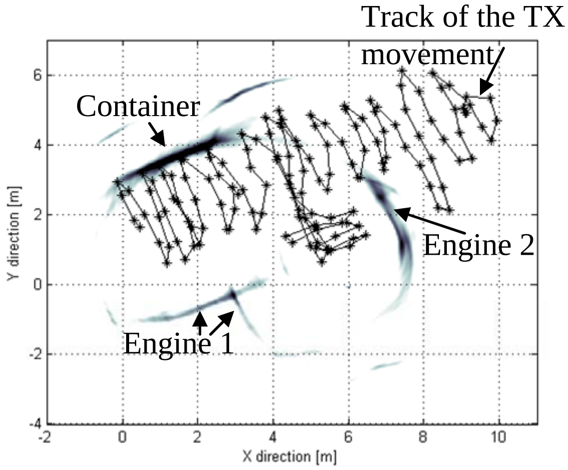

Figure 8 – Reconstructed geometrical structure of the environment with estimated Tx locations

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