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Multidimensional Channel Sounding Instrument, Methods, Results

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Zusammenfassung

Funkkanalübertragungstrecken bilden den zentralen Teil eines jeden Funksystems. Ihre Eigenschaften beeinflussen wesentlich die Leistungsmerkmale gegenwärtiger und künftiger Funksysteme. Gegenstand dieses Aufsatzes bildet die Beschreibung und messtechnische Erfassung der zeit- und frequenzdispersiven sowie zeit- und frequenzselektiven Eigenschaften von Funkübertragungsstrecken. Sie entstehen durch die Überlagerung einer vielzahl von Wellen, die sich am Ort der Empfangsantenne überlagern.

In jüngster Zeit beginnt sich die Einsicht durchzusetzen, dass die auf der Funkübertragungsstrecke entstehende Mehrwegssignalausbreitung nicht als störend, sondern als segensreich verstanden werden muss. Sie stellt eine willkommene Form von Diversität dar, die gegenwärtige wie zukünftige Übertragungsverfahren zur Steigerung der Zuverlässigkeit, Robustheit und spektraler Effizienz der Funkverbindung nutzen können.

Die Auswertung mehrdimensionaler Funkkanalmessungen ermöglicht ein vertieftes Verständnis der relevanten Ausbreitungsmechanismen. Dies stellt eine unabdingbare Voraussetzung für eine zuverlässige Modellbildung zeit- und ortsvarianter Funkübertragungsstrecken dar, wie sie zur Realisierung gegenwärtiger wie zukünftiger Mobilfunksysteme erforderlich sind.

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1 Introduction

Multipath wave propagation causes radio signals to become distorted. As the design and the performance of any wireless communication system depend on the properties of the radio channel, detailed knowledge about the channel's characteristics are indispensable. This is where radio channel sounding and investigations comes into play.

Radio channels have be measured using the pulse sounding [1], frequency sweep, and correlation technique [2]. The correlation method has been widely used because of its interference reduction and Doppler measurement capability [3]-[5]. Cross-polarization coupling investigations of radio signals [6], multi-location sounding for urban vehicle-monitoring systems [7], and multi-frequency sounding using multiple sounders simultaneously [8] have a long standing tradition.

The rapidly growing interest in the directional structure of the propagation channel for wideband signals originated from the discovery that wireless systems do not necessarily suffer but might significantly profit from the inherent diversity offered by the radio environment [9]. Using antenna arrays instead of single antenna elements at one or both ends of a radio link allows to establish multiple independent channels between the terminals. These so called SIMO[1]- (smart antenna), and MIMO[2]-systems, respectively, promise an enhanced spectral efficiency, higher channel capacity, increased reliability of the radio link, and lower interference levels [10].

For the investigation of the spatial properties of wave propagation Kalliola and Vainikainen were first to report a channel sounding technique that scanned the output signals of the array antenna elements sequentially in time [11]. The application of this technique revealed new insights into the spatial wave propagation mechanisms [12]-[15]. This is very important regarding further developments of reliable SIMO, and MIMO channel models needed for future wideband radio systems.

This paper presents a novel architecture for a flexible, integrated wideband vector channel sounder suited for very fast time-variant SISO[3]-, SIMO-, and MIMO radio channel investigations that can be performed simultaneously at multiple-frequencies, -locations, and different polarization of the waves at the transmitter and receiver site. This multi-dimensional channel sounder is based on an exceptional fast data acquisition and storage concept, real-time assessment of virtually any channel data during the ongoing channel measurement in the field, and bus-based modularity allowing full software control of all instrument features.

2 Channel Sounder Requirements

The novel architecture of the channel sounder has been deduced from the requirements originating from

- the temporal and spatial characteristics of the radio environment,
- the peculiarities of wireless communication and navigation systems, and
- the instruments modularity, flexibility, versatility, and ease-of-use within real environments.

The radio channel induced requirements concern the joint estimation of the path-loss, phase, delay, Doppler shift, Angle-of-Departure (AoD), Angle-of-Arrival (AoA), and the transfer matrix $\underline{\mathbf{H}}$ for all polarization of the multipath signals within time frames which are short compared to the coherence time of the radio channel.

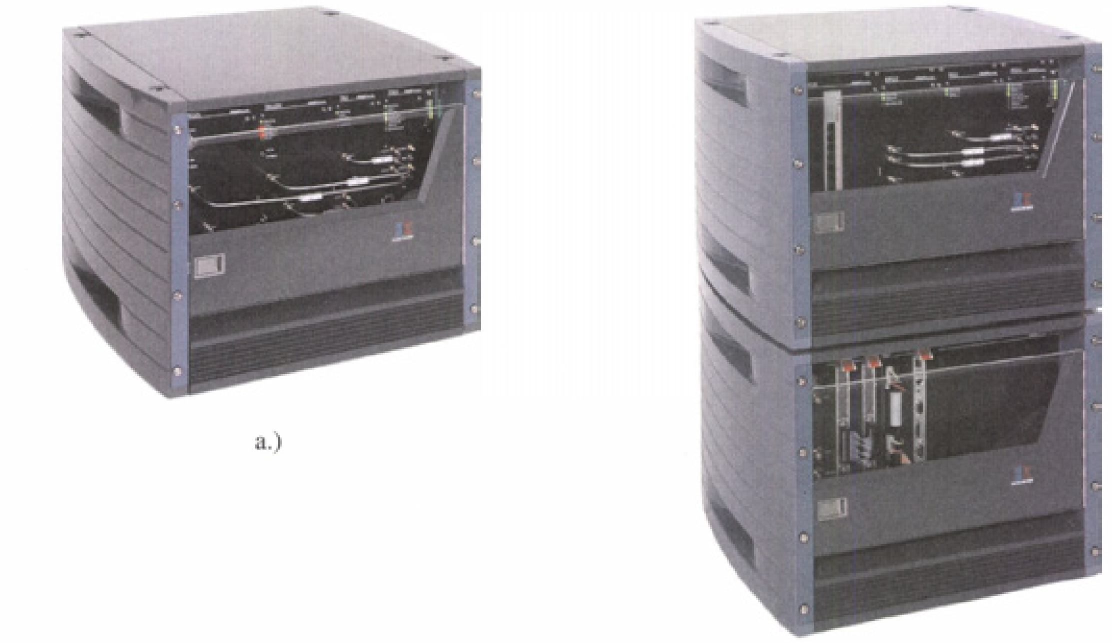
Requirements emerging from terrestrial and satellite radio communication systems, wireless ad-hoc networks, and geolocation systems address the frequency ranges, duplex-modes, hand-over-schemes, multi-location capability, multi-sensor technology, and the typical user mobility profiles of these systems.

[1] Single-Input Multiple-Output.
[2] Multiple-Input Multiple-Output.
[3] Single-Input Single-Output.

3 Novel Channel Sounder Architecture

Basic System Concept

PropSound, the multidimensional channel sounder, is depicted in Fig. 1. It consists of a dedicated transmitter and receiver.



a.)

b.)

Fig. 1: PropSound, Elektrobit's multidimensional channel sounder. a.): transmitter. b.): Receiver with RF/IF part (top), and data acquisition unit (bottom).

Its simplified block schematic is shown in Fig. 2. Basically, the transmitter consists of a control notebook, a code generator, and an antenna switching unit. Apart from a corresponding antenna switching unit, the measuring receiver is made up of a down converter, a data acquisition and storage unit, a real-time display and control notebook, and a post processing software.

The properties of radio channels can be measured by using pulse sounding, frequency sweep techniques or correlation methods. For the measurement of the complex channel impulse response (CIR), the correlation method is chosen within PropSound because of its interference reduction capability and the obtainable recording rates.

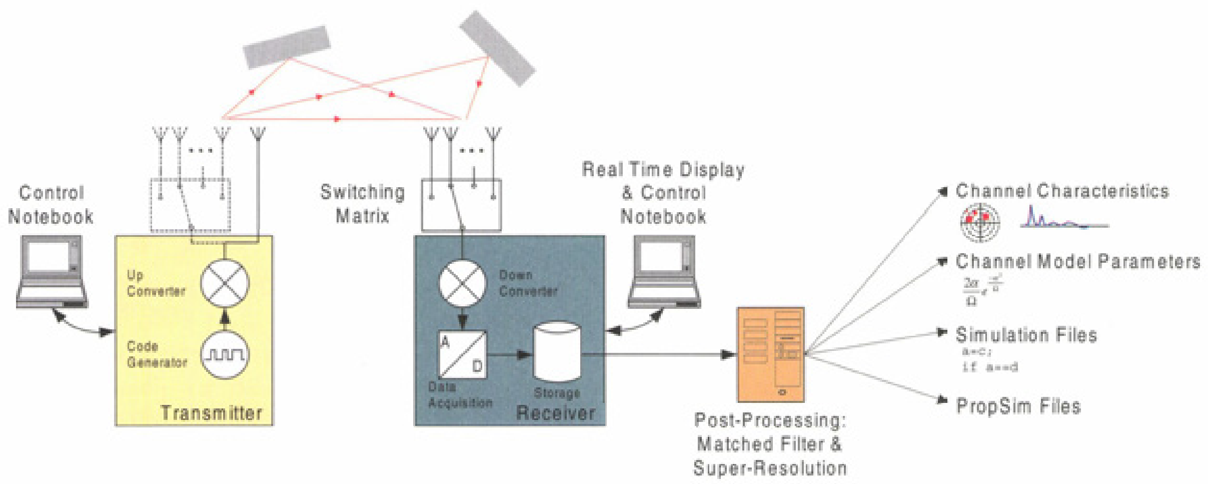


Fig. 2: PropSound block schematic.

Apart from periodically repeated m-sequences any other binary code sequence up to a length of 4096 chips can be generated to BPSK[4] modulate the carrier. To enhance the versatility of the sounder in view of radio test bed applications, any complex baseband signal with bandwidths up to 200 MHz (or more [16]) can be used in the transmitter.

Multi-Dimensional Channel Sounding

The novel timing concept of PropSound paves the way to multi-dimensional channel sounding as it allows time-variant channel measurements within multiple frequency bands (for FDD channels), at multiple locations (for multi-user and geolocation systems), with multiple transmitting and receiving antenna element (for SIMO-, and MIMO-systems), both with multiple polarization. This is accomplished by a TDM[5] technique where the multi-dimensionality of the measurements can be recorded sequentially or non-sequentially within very short time leaving space for permanent storage of the data on a hard disk until the next measurement is triggered. As switching between the TDM channels is kept to the very minimum, changes of sensitive channel parameters such as the phase, the AoD and AoA are also kept small within a single multi-dimensional channel acquisition cycle. Apart from this "sustained" recording mode, a "burst" mode has been implemented to allow for very high measurement rates within a limited period of time. Each measurement is started upon an smart internal or external (e.g. odometer) trigger whose flexibility allows to capture only the minimum required amount of channel data.

The non-sequential TDM scanning technique of the multiple sounding dimensions allows to turn the small but unavoidable phase drifts of oscillators into random phase noise. This is of importance for the spatial channel parameter estimation.

The location of the transmitter and receiver are of importance if both parts of the instrument are moved. To address this problem, the transmitter and receiver either records from its internal GPS receiver location and timing data, location marker information, or odometer data which are stored together with the time-tag information on a mass storage device for later merging them with the recorded measurement data.

High Speed Channel Sounding

The high speed measurement capability in conjunction with the TDM multi-dimensional channel sounding requires a well thought-out storage concept. It is based upon the fact that the duty cycle of a multi-dimensional measurement cycle has to be low in order to measure the time-variant behavior of the radio channel. This leads to the concept of writing the acquired data at full speed into a solid-state memory which is afterwards copied at high speed into a mass storage device before the next measurement has to be triggered. Unprocessed I and Q baseband data are stored because of the efficiency and the reusability of the measured data for different purposes and with different parameter estimation algorithms.

To enhance the data throughput to the mass storage device, multiple data acquisition units can be triggered sequentially in a "round-robin" fashion. This feature works in the sustained and the burst trigger mode of the instrument.

Real-Time Data Assessment

The measured data are simultaneously transferred to a high speed mass storage device for later post-processing and the real-time display unit to allow for on-line data assessment. This real-time quality control of the recorded data is very flexible as any data evaluation features of the post-processing software can be used within real-time display; actually the real-time display uses the same MATLAB code.

The signal processing performed within the post processing software is based on matched filter channel parameter estimation and the SAGE[6] super-resolution algorithm that jointly estimate the path loss, path phase, delay, Doppler shift, AoD, and AoA suffered by the multipath signals [17]. The performance, i.e. the super-resolution capability, accuracy, and convergence rate of the scheme has

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[4] Binary Phase Shift Keying.
[5] Time-Division Multiplex.
[6] Space Alternating Generalized Expectation maximization.

been demonstrated in synthetic and real macro- and pico-cellular environments. The results indicate that the technique outperforms the resolution limitations of classical algorithms such a the Fourier or beam-forming method [18]. Key features of the SAGE-algorithm are:

- No temporal and/or spatial smoothing of the measured data across the array elements are required. Hence, small array with small number of elements allowing fast array scans are sufficient for many applications.
- The algorithm works with nearly any type of array antenna. No restriction on the homogeneity regarding the spacing of the array elements, their matching, their radiation pattern, or their coupling with other array elements matter. Hence, cheap array antennas can be used without compromising the accuracy of the estimated channel parameters.
- The accuracy and number of the estimated path can be traded-of versus computing time. Hence, the real-time display of the strongest paths is possible while performing the channel measurements [19].
- The SAGE-algorithms can be extended to estimate other channel parameters in a straight forward way to adapt it to the task at hand.

The power of the novel channel sounder architecture and the capability of its super-resolution algorithm will be demonstrated in the next section.

4 Measurement Results

Channel measurements have been recorded in Pfäffikon/ZH, and at Elektrobit's premises in Bubikon to demonstrate the PropSound's capabilities. A view from the measurement receiver towards the transmitter which was located in a van is depicted in Fig. 3.

Fig. 3: View from the measurement receiver towards the transmitter located in a van during the measurements recorded in Pfäffikon/ZH.

The magnitude of a measured channel impulse response is shown in Fig. 4. As is visible from this Figure multipath wave propagation from the transmitter to the receiver is present in this environment as there are multiple copies of the transmitted waveform reaching the receiver with propagation delays ranging from about 250 ns to 1 µs.

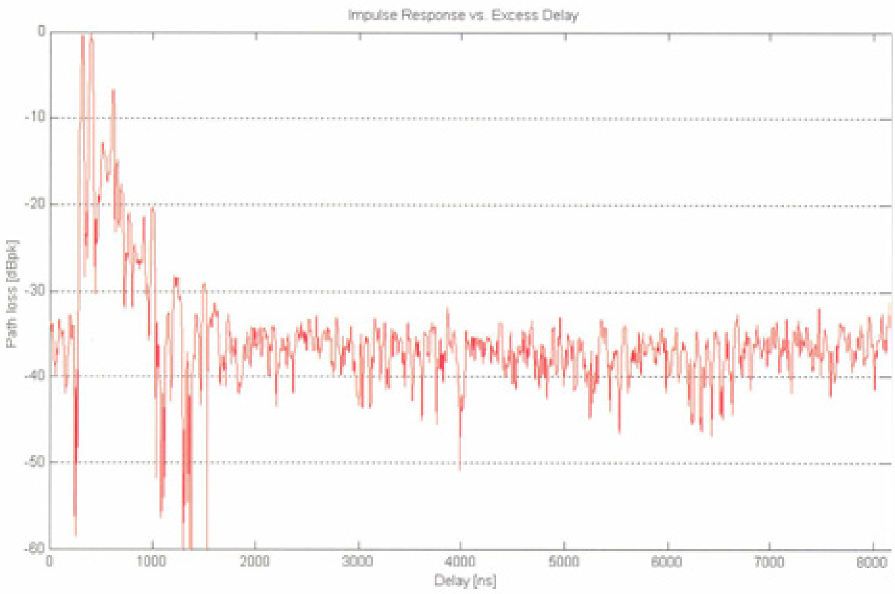

Fig. 4: Magnitude of channel impulse response recorded in Pfäffikon / ZH.

MIMO channel characteristics have been recorded at Elektrobit's premises in Bubikon using a circular array antenna with eight elements at the transmitter site and a 4-by-4 planar array made of patch antenna elements at the receiver site. The results of this investigation are shown in Fig. 5 and Fig. 6.

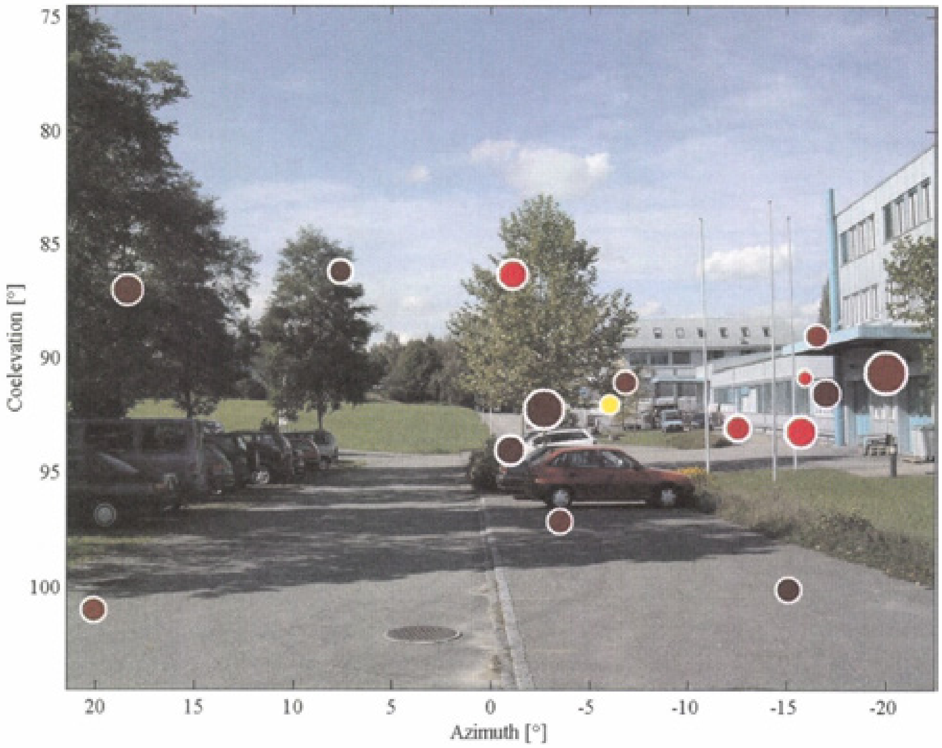

Fig. 5: Angle-of-Arrival (AoA) overlay with array boresight photo with indication of path loss and path delay. Small dots: large path loss. Dark dots: small path delays.

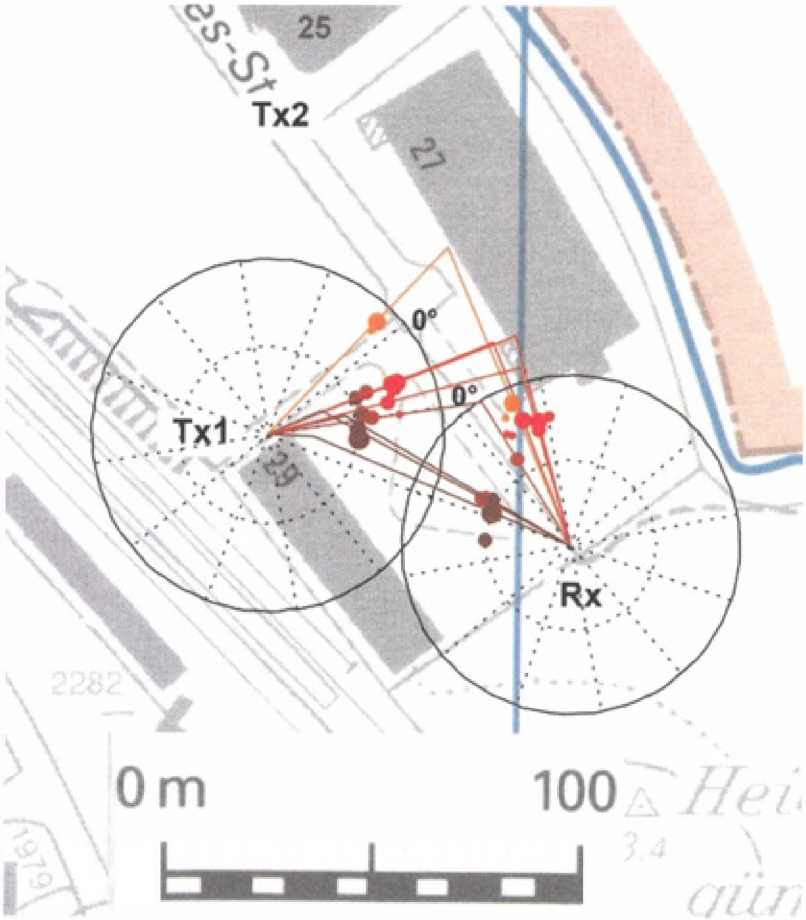

Fig. 6: Map overlay with polar plot of Angle-of-Departure (AoD) and Angle-of-Arrival (AoA) information of multipath signals recorded at Elektrobit's premises in Bubikon. Tx1: Location of the transmitter. Rx1: Location of the measuring receiver. Small dots: large path loss. Dark dots: small path delays

Fig. 5 depicts an AoA data overlay with a photo looking into the direction of the receiving array antennas boresight. Each dot in this picture corresponds to a detected multipath signal reaching the receiver from the respective direction. Small dots indicate signals with large path loss while dark dots have been assigned to signals featuring small path delays. Apart from wave reflections from the buildings, signal scattering and diffraction by trees are clearly visible from this measurement. This indicates that reliable radio channel models should consider the trees within the radio environment.

Fig. 6 shows an overlay of the measured AoD and AoA with the corresponding map. Again, multipath wave propagation is clearly demonstrated by this measurement. As in Fig. 5 small dots indicate large path loss while dark dots were used for small path delays. Apart from the direct line-of-sight path, the combining the measured AoD, AoA and delay information from the detected multipath signals allows to reconstruct the wave propagation paths of waves featuring single bounce from an obstacle.

These measurements clearly demonstrate PropSound's capability to provide super-resolved radio channel parameters which can be successfully validated within real environments. These channel data are a prerequisite for the development and optimization of future radio systems using smart antenna technology or MIMO system architecture.

5 Summary

For performance investigations of SISO-, SIMO-, and MIMO-systems, the development of reliable MIMO channel models, and the understanding of principal propagation mechanisms found in macro-, micro-, and pico-cellular environments, MIMO channel measurement are indispensable. Starting from requirements addressed to a versatile MIMO-channel sounder a novel architecture for a flexible, integrated wideband vector channel sounder including its array antennas are presented and the impact of the signal processing used to estimate the various channel parameters on the design of the array antennas and the performance of the channel sounder are outlined. Based on super-resolved wideband channel measurements, PropSound's capability to provide highest performance and flexibility for radio channel measurements is demonstrated. Together with super-resolution techniques this sounder allows accurate radio channel measurements for SISO, SIMO, MIMO, geolocation, and multi-user radio systems.

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