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A Novel Architecture for MIMO Spatio-Temporal Channel Sounder

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SUMMARY Implementation of Multi-Input Multi-Output (MIMO) channel sounder is considered, taking hardware cost and realtime measurement into account. A remarkable difference between MIMO and conventional Single-Input Multi-Output (SIMO) channel sounding is that the MIMO sounder needs some kind of multiplexing to distinguish transmitting antennas. We compared three types of multiplexing TDM, FDM, and CDM for the sounding purpose, then we chose FDM based technique to achieve cost effectiveness and realtime measurement. In the framework of FDM, we have proposed an algorithm to estimate MIMO channel parameters. Furthermore the proposed algorithm was implemented into the hardware, and the validity of the proposed algorithm was evaluated through measurements in an anechoic chamber.

key words: *mobile propagation, channel sounder, MIMO channel response, channel parameter estimation, hardware implementation*

1. Introduction

MIMO communication system is considered to play a key role in the 4th generation mobile communication system that will realize bit rate as high as 100 Mbps (e.g., [1]). This is because the MIMO communication system can increase the channel capacity without expanding the required frequency bandwidth (e.g., [2]). Since the performance of MIMO communication system depends on the directional as well as the temporal behavior of the channel, field measurement data of MIMO channel is strongly required to develop and evaluate the MIMO communication systems.

There are two usages of the field measurement data. One is a raw measurement data, and the other is a parametric data. The MIMO channel is considered to be parameterized by direction of arrival (DOA), direction of departure (DOD), and time of arrival (TOA). The raw measurement data is only devoted to the performance evaluation [3], but parametric data is for both development and performance evaluation since it is independent on the configurable parameters in the communication system such as antenna directivity, array configuration, and signal bandwidth. Therefore it is very important to measure the MIMO channel parameters to develop the MIMO communication systems. In addition to that, if these channel parameters can be measured simultaneously, not only the spatial and temporal spreading of the channel, but also the mutual relationship between the spatial and temporal characteristics of the channel can be analyzed. Thus, we need such a kind of channel parameter measurement system which we call MIMO spatio-temporal channel sounder.

The requirements for the MIMO spatio-temporal channel sounder are as follows:

- Simultaneous estimation of DOA, DOD, and TOA
- Realtime measurement with respect to the coherent time that is a function of Doppler frequency which is not only caused by the movement of the mobile terminal but also the movement of scatterers such as surrounding vehicles
- Large dynamic range of measurement system
- Cost effective hardware

Recently such a channel sounder is proposed in [4], [5]. But none of them satisfy all of the above requirements. It is because they are just an extension of conventional SIMO channel sounder [6], [7], in other words it is a sequential SIMO channel sounding. In this paper, we propose a full MIMO channel sounder.

A remarkable difference between MIMO and SIMO channel sounding is that the MIMO sounder needs some kind of multiplexing to distinguish transmitting antennas. In [4], the first prototype of MIMO channel sounder using time division multiplexing (TDM) technique, namely switching and synthetic aperture array antenna, was proposed. Since it used the synthetic aperture array antenna, the environment must be static during the measurement, or all the effects caused by moving objects need to be eliminated by using Doppler filter. In other words, it is far from realtime measurement. In this paper, we systematically compared three types of multiplexing technique, TDM, FDM (frequency division multiplexing), and CDM (code division multiplexing), from the sounding point of view. Then we found that the FDM based technique can achieve all of the above requirements. In the FDM based technique we have proposed:

- New transmitting signal configuration (we call it multi-tone FDM)

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- New parameter estimation algorithm (extension of multidimensional superresolution algorithms [8]–[10])

Furthermore the proposed algorithm was implemented into the hardware, and the validity of the proposed algorithm was evaluated through measurements in an anechoic chamber.

This paper is organized as follows. Section 2 provides the formulation of MIMO channel response vector. In Sect. 3 measurement technique of MIMO channel is discussed and then we propose a new technique. The proposed technique is implemented into the hardware in Sect. 4. The proposed algorithm and implemented hardware are validated through the measurement in Sect. 5. Finally, Sect. 6 gives a conclusion of this paper.

Mathematical notations used in this paper are as follows:

$\boldsymbol{X}^T$: transposition
$\otimes$: Kronecker product
$\odot$: Hadamard product

Finally the operator vec$\{\cdot\}$ maps a matrix to a vector by stacking the columns of the matrix.

2. MIMO Channel Response

Typical environment for MIMO channel sounding is illustrated in Fig. 1. Consider a m_s-element transmitting array antenna at the mobile station MS (Tx), and a m_r-element receiving array antenna at the base station BS (Rx). The channel is a superposition of multipath components. Each path is departed from the transmitting array with an azimuth angle θ_i^s and is arriving at the receiving array with an azimuth angle θ_i^r, where i is an index of multipath components. Between Tx and Rx, each path has a delay time τ_i and complex amplitude γ_i that is a function of scattering and propagation coefficients. A $m_r \times m_s$ channel matrix $\boldsymbol{H} \in C^{m_r \times m_s}$ at the center frequency of f_c can be expressed as

$$\boldsymbol{H} = \sum_i \gamma_i(t) e^{-j2\pi f_c \tau_i} \boldsymbol{a}_r(\theta_i^r)(\boldsymbol{a}_s(\theta_i^s))^T, \quad (1)$$

where $\boldsymbol{a}_s(\theta)$ and $\boldsymbol{a}_r(\theta)$ are transmitting and receiving

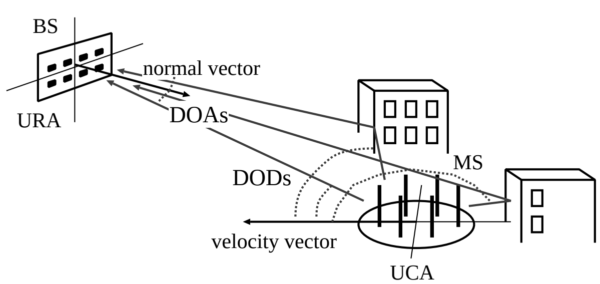

Fig. 1 MIMO channel sounding environment.

array response vectors, for the plane wave impinging from the azimuth angle θ, respectively. It should be noted that the complex amplitude $\gamma_i(t)$ is time variant due to the Doppler frequency.

For convenience to treat a multidimensional problem, the channel matrix $\boldsymbol{H} \in C^{m_r \times m_s}$ is reformulated to a $m_r \cdot m_s$ dimensional vector $\boldsymbol{h} \in C^{m_r \cdot m_s}$ by using vec$\{\cdot\}$ operator as

$$\begin{aligned}\boldsymbol{h} &= \mathrm{vec}\{\boldsymbol{H}\} \\ &= \sum_i \gamma_i(t) e^{-j2\pi f_c \tau_i} \boldsymbol{a}_r(\theta_i^r) \otimes \boldsymbol{a}_s(\theta_i^s). \end{aligned} \quad (2)$$

As the next step, frequency response vector $\boldsymbol{a}_f(\tau)$ is introduced for the wideband measurement. Finally the three dimensional channel response vector $\boldsymbol{h} \in C^{m_r \cdot m_s \cdot m_f}$ is formulated as

$$\boldsymbol{h} = \sum_i \gamma_i(t) \boldsymbol{a}_r(\theta_i^r) \otimes \boldsymbol{a}_s(\theta_i^s) \otimes \boldsymbol{a}_f(\tau_i). \quad (3)$$

In this formulation, the MIMO channel parameters are DOA (θ_i^r), DOD (θ_i^s), and TOA (τ_i). This equation has a simple form that is easily extendable to include elevation angle estimation.

If we consider an uniform linear, rectangular, or circular array (ULA, URA, or UCA) antenna and uniform m_f frequency sample points, Eq. (3) can be considered as multidimensional harmonic retrieval problem. Therefore the parameter sets $\{\theta_i^r, \theta_i^s, \tau_i\}_i$ can be simultaneously estimated by using multidimensional superresolution algorithms. In this paper we employed 3-D Unitary ESPRIT [9], [10].

If we consider the real channel environment, it is impossible to distinguish all of the multipath components even by using the superresolution algorithms due to the finiteness in the signal to noise ratio, antenna aperture, and signal bandwidth. Since the measurement data is devoted to the development of the MIMO communication system, we do not need the MIMO channel sounder with infinite resolution. The data measured with finite resolution that satisfies requirements for development of the MIMO communication systems is enough. On the other hand, we have to design the channel sounder to achieve the best possible performance under the given physical restrictions. Such an analysis was done in [11].

3. Measurement Technique of MIMO Channel

Again recall Eq. (1) as a channel response matrix. In the point frequency measurement, the received signal vector $\boldsymbol{y}$ is described as

$$\boldsymbol{y}(t) = \boldsymbol{H}\boldsymbol{s}(t) + \boldsymbol{n}(t) \in C^{m_r}, \quad (4)$$

where $\boldsymbol{s}(t) \in C^{m_s}$ is a transmitting signal vector and $\boldsymbol{n}(t) \in C^{m_r}$ is a noise vector. In the wideband measurement, $\boldsymbol{H}$ is characterized with another parameter, delay τ, and is convolved with transmitting signal sequence $\boldsymbol{s}$. Anyway, the observable signal is only the superposition of contributions from all transmitting antennas. Therefore some kind of multiplexing technique is needed to implement the MIMO channel sounder.

By using an analogy with the multi-user communication scenario, three types of multiplexing are conceived, namely TDM, FDM, and CDM. Comparison of these multiplexing techniques for sounding purpose is shown as follows in terms of realtime measurement, hardware cost, and major drawbacks.

- TDM
  - Realtime measurement → poor
    Measurement period is m_s times baseband signal period plus guard interval for excess delay and switching.
  - Hardware cost → excellent
    Only one transmitter channel is needed.
  - Major Drawback
    Absolute time synchronization between transmitter and receiver is required.
- CDM
  - Realtime measurement → excellent
    Measurement period does not depend on m_s.
  - Hardware cost → poor
    It needs m_s transmitter channels.
  - Major Drawback
    Dynamic range of the system is limited by m_s due to the cross-correlation between different codes.
- FDM
  To accomplish the wideband measurement by using FDM technique, we introduced a new transmitting signal configuration as illustrated in Fig. 2. In the case of two Tx antennas, firstly a multi-tone signal with tone separation of Δ_F is prepared. Then this signal and frequency shifted replica of the signal are multiplexed through the transmission from different antennas. The frequency shift Δ_f should be a fraction of Δ_F to keep an orthogonality between all of the tones. Smaller Δ_f needs larger period of Discrete Fourier Transform (DFT) to separate multiplexed signals in the receiver side. Therefore, $\Delta_f = \Delta_F/m_s$ is the most effective way for multiplexing in the case of m_s transmitting antennas. We call this technique as multi-tone FDM (MTFDM).
  - Realtime measurement → good
    Measurement period is m_s times baseband signal period.
  - Hardware cost → good
    It requires m_s local oscillators, but one baseband signal generator.
  - Major Drawback
    Some modification is needed for the data model described in Sect. 2, since the frequency sample points in each transmitting antenna are different.

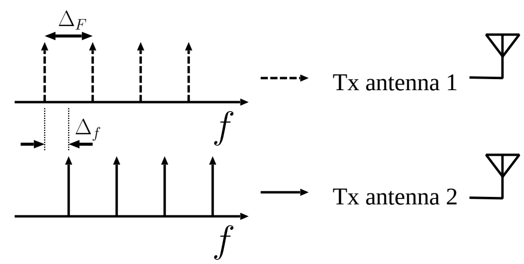

Fig. 2 Multi-tone FDM for MIMO sounding.

We successfully solved the drawback in FDM technique as follows. The newly introduced concept is a FDM response vector $\boldsymbol{a}_{FDM}(\tau_i) \in C^{m_s}$ defined as

$$\boldsymbol{a}_{FDM}(\tau_i) \triangleq [1, e^{-j2\pi\Delta_f\tau_i}, \cdots, e^{-j2\pi(m_s-1)\Delta_f\tau_i}]^T. \quad (5)$$

By using this vector, the transmitting array response vector is rewritten as

$$\boldsymbol{a}'(\phi_i^s) = \boldsymbol{a}_s(\theta_i^s) \odot \boldsymbol{a}_{FDM}(\tau_i) \in C^{m_s}, \quad (6)$$

where ϕ_i^s is a function of θ_i^s and τ_i. This formulation is a natural way to describe that the frequency sample points for each transmitting antenna are shifted by the integer multiple of Δ_f. Finally the channel response vector for FDM based MIMO system is written as

$$\boldsymbol{h}' = \sum_i \gamma_i(t)\boldsymbol{a}_r(\theta_i^r) \otimes \boldsymbol{a}'_s(\phi_i^s) \otimes \boldsymbol{a}_f(\tau_i). \quad (7)$$

Equation (7) can be considered again as a multi-dimensional harmonic retrieval problem, so that the parameter sets $\{\theta_i^r, \phi_i^s, \tau_i\}_i$ can be simultaneously estimated in the same way describe in Sect. 2. It means θ^s is calculated from the estimated parameters, ϕ^s and τ. Thus, the channel parameters can be estimated even by using the different frequency sample points in each transmitting antenna.

If the above solution is considered, there is no weakness in the FDM based technique, while at the same time, it can achieve both cost effectiveness and realtime measurement. Therefore we choose this technique for the hardware implementation.

4. Hardware Implementation

Based on the discussion in Sect. 3, we implemented the FDM based MIMO channel sounder. It is a modified version of the SIMO channel sounder proposed in [12], [13]. For simplicity to confirm the algorithm proposed in Sect. 3, we employed 2 elements linear patch

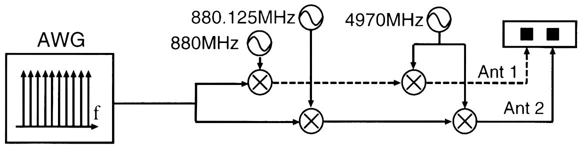

Fig. 3 Transmitter block diagram.

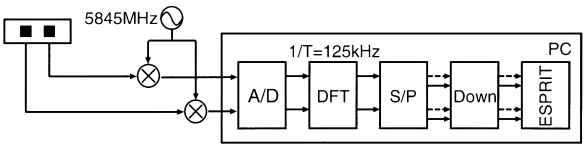

Fig. 4 Receiver block diagram.

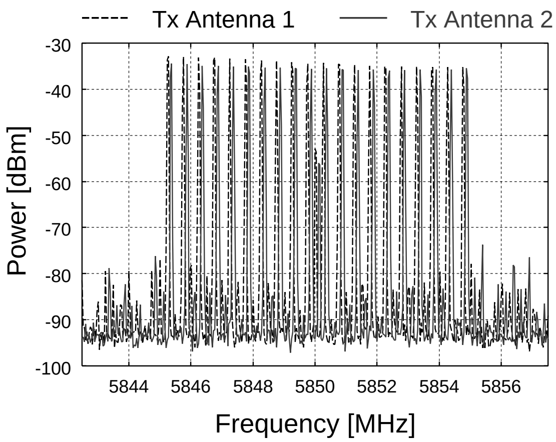

Fig. 5 Frequency spectrum of transmitting signals.

Table 1 Configuration of multi-tone signal.

# of tones	20
tone separation	500 [kHz]
bandwidth	9.5 [MHz]

array antenna both in Tx and Rx. Block diagrams of transmitter and receiver are shown in Fig. 3 and Fig. 4 respectively. In this paper, we concentrate on the MTFDM configuration, whereas the detailed hardware setup is described in [12], [13].

Baseband multi-tone signal is generated by using Arbitrary Waveform Generator (AWG). Configuration of the multi-tone signal is described in Table 1. To implement the proposed MTFDM, two IF oscillators were introduced. We employed 880 [MHz] and 880.125 [MHz] for IF. We used a 125 [kHz] shift in frequency instead of 250 [kHz] to avoid the effect of DC offset. Finally, these signals are up-converted to 5.85 [GHz] band and transmitted from each antenna. Transmitting signal spectrum is shown in Fig. 5.

In the receiver side, we employed the low-IF architecture, where IF=5 [MHz]. Then these down-converted signals are sampled by using 20 Msps A/D converter with 12 bit resolution. In the digital signal processor, DFT at the rate of 125 [kHz] is performed to separate the multiplexed signals. Finally the 3-D Unitary ESPRIT algorithm is applied to the extracted multi-tone signals.

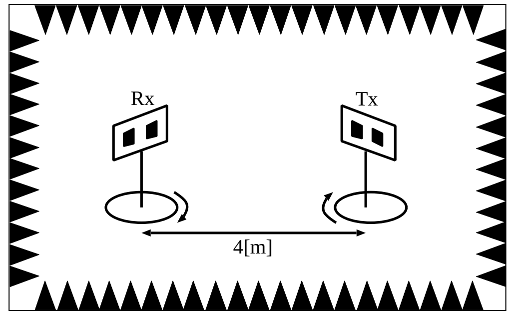

Fig. 6 Measurement setup in the anechoic chamber.

5. Measurement Example

Measurement experiment was conducted in an anechoic chamber to validate the FDM based algorithm proposed in Sect. 3 and the FDM based hardware implemented in Sect. 4. Measurement setup is illustrated in Fig. 6. In this situation, we have assumed that the anechoic chamber is perfectly configured, so that only a direct wave exists between Tx and Rx. The most simple environment, with the direct path only, is enough to confirm the FDM based algorithm, since the validation in the multipath environment was done in e.g. [5] by using TDM based algorithm. The resolution of these two algorithms is considered to be the same theoretically. Both array antennas were located on the rotators separated by a distance of 4 [m]. Both rotators were turned around at 15 [deg] intervals, Rx rotator angles: $\{-30, -15, 0, 15, 30\,[\mathrm{deg}]\}$, Tx rotator angles: $\{-15, 0, 15\,[\mathrm{deg}]\}$, and measurements were conducted for each pair of angles. This measurement sequence was repeated 5 times to assure the repeatability. Calibration of the hardware was performed by the simple back-to-back calibration. Throughout the measurements, we took 30 times of snapshot, and the path gain, $\mathrm{E}[|\gamma|^2]$, to noise, σ^2, ratio was about 25 [dB].

All of the measurement results with respect to the DOA and DOD are shown in Fig. 7. If the estimated results are on the every 15 [deg] grid, it means good performance of the measurement is achieved in terms of DOA, DOD, and indirectly TOA through Eq. (6). From this figure, we could confirm the validation of the proposed algorithm and implemented hardware. It is noted that the slight degradation of the estimates is due to the set up and calibration error during the measurements.

6. Concluding Remarks

MIMO channel sounding is an attractive way to mea-

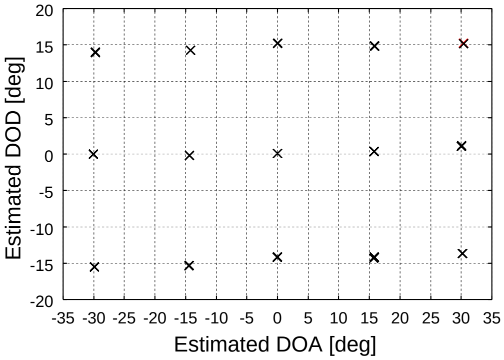

Fig. 7 Experimental results in the anechoic chamber.

sure the propagation mechanism in the mobile cellular environment. In this paper, an architecture for MIMO spatio-temporal channel sounder was thoroughly investigated. After the considerable discussions about techniques of multiplexing to distinguish the transmitting antennas, the FDM based architecture was chosen to achieve cost effectiveness and realtime measurement. In the framework of FDM, we have proposed a new transmitting signal configuration and a new algorithm to estimate the MIMO channel parameters DOA, DOD, and TOA simultaneously. We confirmed the validity of the FDM based architecture through the measurement in an anechoic chamber.

To accomplish the development of MIMO channel sounding system, further investigation for following items will be required. First one is an optimization of MIMO array configuration, and the other is a novel calibration for MIMO sounding system.

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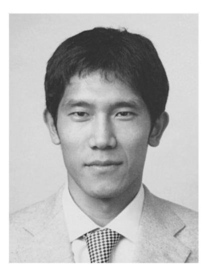

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