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DEVELOPMENT OF HIGH RESOLUTION MIMO CHANNEL SOUNDER FOR THE ADVANCED MODELING OF WIRELESS CHANNELS

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This paper describes the development of the multi-input multi-output (MIMO) channel sounder which can jointly estimate the direction of departure (DOD), the direction of arrival (DOA) and the delay time of arrival (DTOA), for the advanced modeling of wireless channels. The algorithm and the hardware architecture are described, as well as the experimental results using the prototype.

1 Introduction

Recently, the utilization of the MIMO channel has been focused in the wireless communication systems, since it has a high potential to drastically increase the channel capacity [1, 2, 3]. Since the channel capacity much depends on the channel response, it is very important to know the MIMO channel properties in the real propagation environments.

Recently, double directional (MIMO) channel sounding techniques have been proposed [4, 5]. In the double directional sounding system, array antennas at both BS and MS are employed as in Fig. 2. In this scenario not only the DOA but also the direction of departure (DOD) are considered simultaneously. The MIMO channel sounder is superior to the conventional single-input multiple-output (SIMO) spatio-temporal channel sounder, as the former can distinguish each path at both sides, which results in the higher resolution [6].

However, the MIMO sounder needs some kind of multiplexing technique to distinguish the transmit antennas. The first prototype of MIMO channel sounder in Ref. [4] used the switching array antenna, and the time division multiplexing (TDM) technique was used. Since it used the synthetic aperture array antenna, the environment must be static during the measurement, or all moving objects are eliminated by using Doppler filter. In other words, it is far from the real-time measurement.

In this paper, we propose the frequency division multiplexing (FDM) technique for the transmitter of the MIMO channel sounder. The FDM based technique is cost effective and suitable for the real-time measurement. In the FDM framework, we propose a new algorithm to estimate the MIMO channel parameters, DOAs, DODs, and DTOAs, simultaneously. The proposed algorithm was implemented in the hardware which was a extended version of the SIMO channel sounder developed by the authors [7,

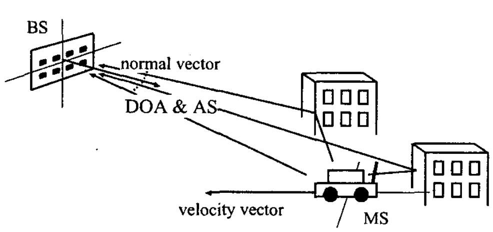

Figure 1: Mobile propagation scenario

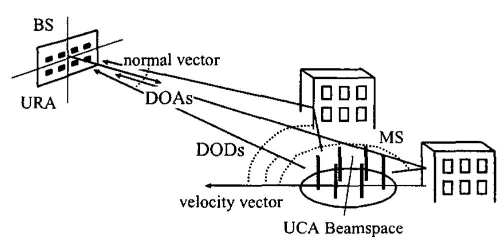

Figure 2: MIMO channel sounding

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8, 9, 10], and the validity of the proposed algorithm was evaluated through measurements in an anechoic chamber.

Mathematical notations used in this paper are as follows: E$[\cdot]$ is expectation, $\mathbf{X}^H$ and $\mathbf{X}^T$ are Hermitian transpose and transpose of $\mathbf{X}$ respectively, $\mathbf{X}^{\perp}$ is the projection operator onto the complement of the space spanned by $\mathbf{X}$, and $\hat{\mathbf{X}}$ is an estimate of $\mathbf{X}$. $\otimes$ is Kronecker product, and $\odot$ is Hadamard product, i.e. element-by-element product. Finally the operator vec$\{\cdot\}$ maps a matrix to a vector by stacking the columns of the matrix.

2 MIMO Channel Response

Consider an m_s element transmitting (Tx) array antenna at the MS, and an m_r element receiving (Rx) array antenna at the BS. An $m_r \times m_s$ channel matrix $\mathbf{H} \in C^{m_r \times m_s}$ at the center frequency of f_c can be expressed as

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

where $\mathbf{a}_s(\theta^s)$ and $\mathbf{a}_r(\theta^r)$ are array response vectors of transmitting and receiving array respectively, and $\gamma(t)$ is a complex amplitude of each path and is time variant due to the Doppler frequency. In this formulation, the MIMO channel parameters are the DOA, θ^r, the DOD, θ^s, and the DTOA, τ. Finally the channel matrix $\mathbf{H}$ is a superposition of resolvable path indexed by i.

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

$$\mathbf{h} = \text{vec}\{\mathbf{H}\} = \sum_i \gamma_i(t) e^{-j2\pi f_c \tau_i} \mathbf{a}_r(\theta_i^r) \otimes \mathbf{a}_s(\theta_i^s). \tag{2}$$

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

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

This equation has a simple form that is easily extendable to another dimension as elevation angle estimation.

If we consider an uniform linear, rectangular, or circular array (ULA, URA, or UCA) antenna and uniform m_f frequency sampling, Eq. (3) can be considered as multidimensional harmonic retrieval problem. Therefore the parameter sets $\{\theta^r,\ \theta^s,\ \tau\}$ can be simultaneously estimated by using multidimensional superresolution algorithms. In this paper, we employed 3-D Unitary ESPRIT [11] using chain pairing (CP) [12].

3 Measurement Technique of MIMO Channel

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

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

where $\mathbf{s}(t) \in C^{m_s}$ is a transmitting signal vector and $\mathbf{n}(t) \in C^{m_r}$ is a noise vector. In the wideband measurement, $\mathbf{H}$ has another dimension of delay τ and is convolved with transmitting signal sequence $\mathbf{s}(t)$. It is noted that the received signal at each Rx antenna is the superposition of the signals from all Tx antennas, in the MIMO channel measurement. Therefore some kind of multiplexing technique is needed to distinguish the transmitted signals from different antenna elements.

By using an analogy with the multi-user communication scenario, three types of multiplexing are conceived, namely time division multiplex (TDM), frequency division multiplex (FDM) and code devision multiplex (CDM). After the comparison of these multiplexing techniques in terms of the real-time measurement and the hardware cost, the authors have concluded that FDM is most appropriate.

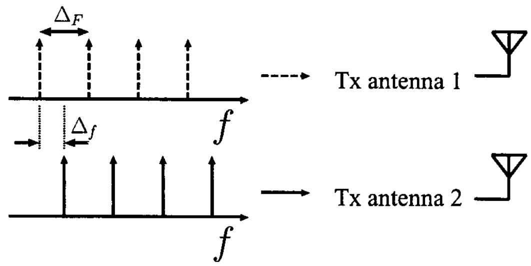

Figure 3: Frequency division multiplexing for MIMO sounding

To accomplish the wideband measurement by using FDM technique, the authors propose a new concept as illustrated in Fig. 3. For simplicity, the case of two Tx antennas is considered. A multi-carrier signal with carrier separation of Δ_F is prepared. 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 the carriers. Since the smaller Δ_f needs larger period of Discrete Fourier Transform (DFT) to separate multiplexed signals in the receiver, $\Delta_f = \Delta_F/m_s$ is chosen as a most effective way in the case of m_s transmitting antennas. We call this technique as multi-carrier FDM (MC-FDM).

It is noted that some modification is needed for the data model described in Sect. 2, since the frequency sample points for each transmitting antenna are different. To solve this problem, a FDM response vector $\mathbf{a}_{FDM}(\tau_i) \in C^{m_s}$ is newly introduced, which is defined as

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

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

$$\mathbf{a}'_s(\psi_i^s) = \mathbf{a}_s(\theta_i^s) \odot \mathbf{a}_{\text{FDM}}(\tau_i) \in C^{m_s}, \tag{6}$$

where ψ_i^s is a function of θ_i^s and τ_i. In other words, the frequency sample points for each transmitting antenna are shifted by the integer multiple of Δ_f. Finally, the channel response vector for MC-FDM based MIMO system is written as

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

Eq. (7) can be considered again as multi-dimensional harmonic retrieval problem, so that the parameter sets $\{\theta^r, \psi^s, \tau\}$ can be simultaneously estimated in the same way describe in Sect. 2. Of course, θ^s is calculated from ψ^s and τ.

4 Hardware Implementation

Based on the discussion in Sect. 3, the authors implemented the FDM based MIMO channel sounder. It is a modified version of the SIMO channel sounder proposed in [10]. For simplicity to confirm the algorithm proposed in Sect. 3, we employed 2 elements linear array of rectangular patch antennas both in Tx and Rx. Block diagrams of transmitter and receiver are shown in Figs. 4 and 5,respectively. In this paper, we concentrate on the MC-FDM configuration, whereas the detailed hardware setup is described in [8, 10].

Baseband multi-carrier signal is generated by using arbitrary waveform generator (AWG). The number of carriers is 20, carrier separation is 500 kHz and the total bandwidth is 9.5 MHz. To implement the proposed MC-FDM, two intermediate frequency (IF) oscillators were introduced. We employed

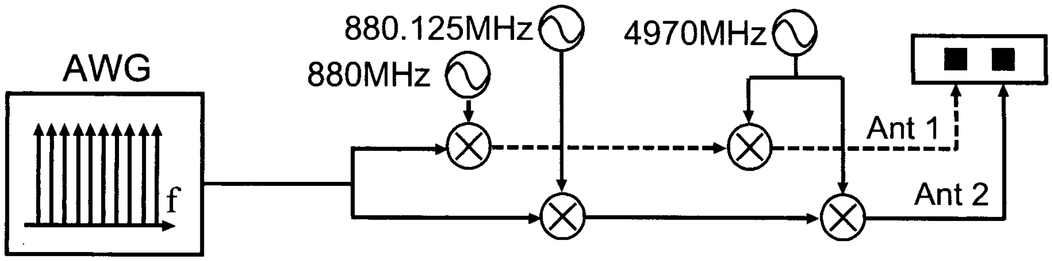

Figure 4: Transmitter block diagram

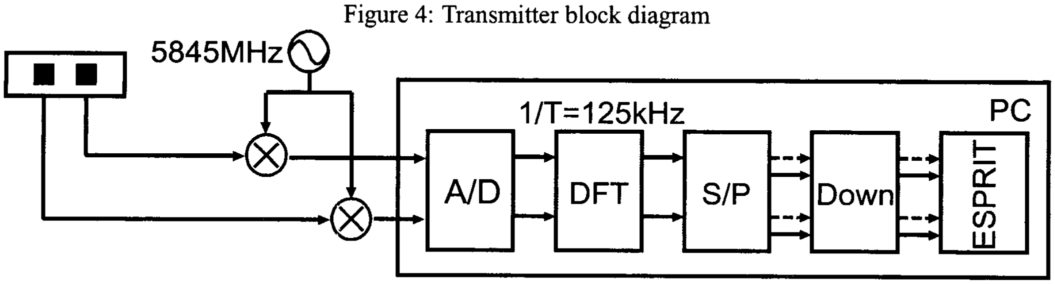

Figure 5: Receiver block diagram

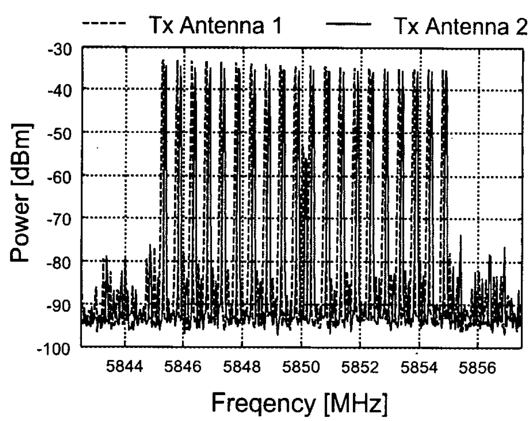

Figure 6: Frequency spectrum of transmitting signal

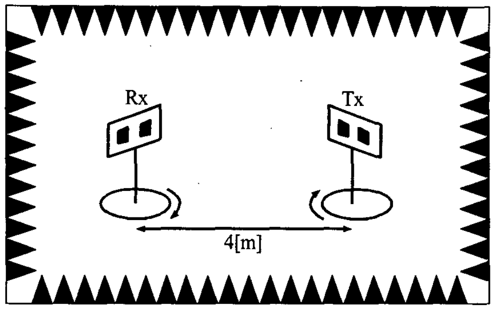

Figure 7: Measurement setup in the anechoic chamber

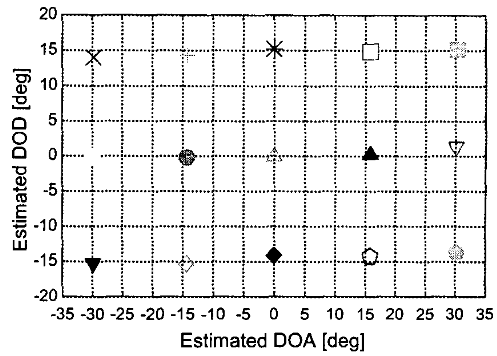

Figure 8: Experimental results in the anechoic chamber

880 MHz and 880.125 MHz for IFs. We used 125 kHz shift of 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 two antenna elements. Transmitting signal spectra for these two antennas are shown in Fig. 6.

In the receiver side, we employed the low-IF architecture, i.e. IF=5 MHz. Then these down-converted signals are sampled by using 20 Msps 12 bit A/D converter. In the digital signal processor, the 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-carrier signals.

5 Experiments in the Anechoic Chamber

Experiments were conducted in an anechoic chamber to validate the algorithm proposed in Sect. 3 and the hardware implemented in Sect. 4. Measurement setup is illustrated in Fig. 7. In the experiments, only a direct path existed between Tx and Rx. Both array antennas were located on the rotators separated by a distance of 4 m. Both antennas were rotated every 15 deg., i.e., Rx rotator angles were $\{-30, -15, 0, 15, 30$ deg.$\}$ and Tx rotator angles were $\{-15, 0, 15$ deg.$\}$. The 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 snapshots. The signal to noise ratio per each element-pair was about 25 dB.

All of the measurement results with respect to the DOA and DOD are shown in Fig. 8. Since all the results are almost on the grid points, it is proved that the good performance of the measurement was achieved in terms of DOA, DOD, as well as DTOA. The small degradation of the estimates is due to the errors in the angle position and the calibration during the measurements.

6 Concluding Remarks and Future Works

This paper presented the high resolution MIMO channel sounding and its implementation by using MC-FDM. Experimental demonstrations show the effectiveness of the proposed scheme.

Although not mentioned in the paper, it was found through the theoretical analysis that MIMO channel sounding achieves higher performance compared with a conventional SIMO sounding [6]. Therefore, this sounder is useful as well for the SIMO channel modeling at base station, which had been only achieved in the average sense by measuring the correlation characteristics.

It is also noted that the site-specific and stochastic MIMO channel model can be achieved by applying the random-phase approach [13, 5] to the experimental results, since the propagation paths are resolved, and the motion of the MS results in the phase rotation of each path.

Since the experiments have been conducted by using the prototype sounder, the reduction of the size is necessary for the field test, which is left for the future work.

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