Calibration Techniques for Fully Parallel 24 × 24 MIMO Sounder

Yuyuan Chang, Yohei Konishi, Minseok Kim and Jun-ichi Takada
Graduate School of Science and Engineering, Tokyo Institute of Technology
2-12-1-S6-4, Ookayama, Meguro-ku, Tokyo 152-8550, Japan, chang@ap.ide.titech.ac.jp

1. Introduction

Multiple-input multiple-output (MIMO) systems have attracted lots of attentions, for their potential for high gain in channel capacity. For evaluating the performance of MIMO systems in more practical situations, more accurate channel models are necessary; and channel measurement is necessary to estimate the parameters of the channel models [1] [2]. In [2], we developed a fully parallel wideband MIMO channel sounding system at 11GHz with 400MHz bandwidth, which utilized software defined radio (SDR) architecture and is considered more suitable for real-time evaluation of link-level performance and channel properties, comparing with switching-based time division multiplexing (TDM) sounder, that has been commonly used [3]. However, one of the drawbacks of the fully parallel MIMO channel sounder system is that it needs complex procedures of baseband circuit adjustment, radio frequency (RF) circuit compensation, and back-to-back (B2B) calibration measurement, comparing with switching-based system; and the complexity increases with the numbers of transmit (Tx) and receive (Rx) channels. Since currently, the sounder system developed in [2] has been extended into 24 × 24 MIMO sounder, it becomes a very serious problem that it will take very long time to carry out the B2B calibration measurement for all possible MIMO connections. In this paper, automatic system calibration schemes are introduced and a simplified B2B calibration method is also proposed to shorten the measurement time.

2. Configuration of the 24 × 24 MIMO Sounder

The 24 × 24 MIMO sounder utilizes the testing multitone signal with bandwidth of 400 MHz at 11 GHz; and the number of sinusoidal tones is 2048 in the testing signal. As shown in Fig. 1, the system consists of 3 boxes of transmitter (BTx) and receiver (BRx) in the Tx and Rx sides, respectively, for the measurement flexibility [2]. The boxes are controlled by a master PC via local area network (LAN) and the digital circuit is synchronized by the external clock of 10 MHz that generated by the external clock synthesizer based on the atomic clock. The 11 GHz local oscillator (LO) signals input to the RF circuits of the Tx and Rx boxes are also generated by the external synthesizer with very low phase noise. Each BTx or BRx has 8 Tx or Rx channels, each of which has its own baseband circuit and RF circuit. The baseband circuit of each channel includes two analogue to digital converters (ADC) in the Rx or digital to analogue converters (DAC) in the Tx, for the in-phase and quadrature (IQ) signals; and the analogue ports are connected to the input ports of quadrature down-converter (in Rx) or the output ports of quadrature up-converter (in Tx) in the RF circuit of each channel. In other words, each BRx has 16 baseband ADC inputs connected to the baseband outputs of RF circuit with 8 RF inputs; and each BTx has 16 baseband DAC outputs connected to the baseband inputs of RF circuit with also 8 RF outputs.

3. Calibration Techniques

For reducing the effects of the impairments of the hardware including the baseband and RF circuits, to the measured MIMO wireless channel, calibration processes for the system is necessary. In this section the automatic calibration techniques is introduced.

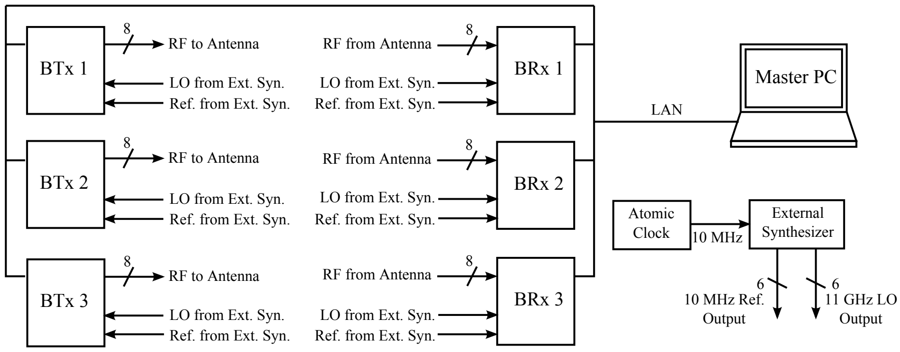
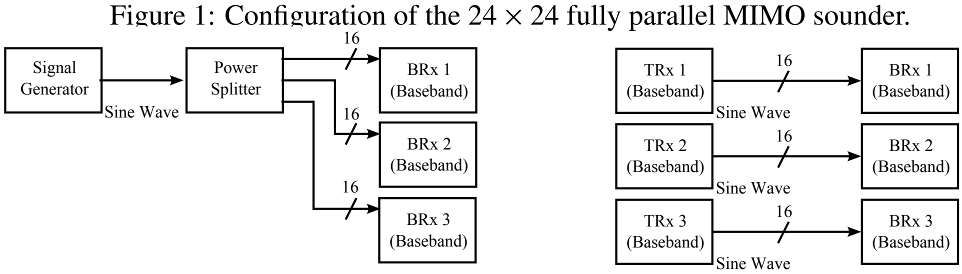


Figure 1: Configuration of the 24 × 24 fully parallel MIMO sounder.



(a) Baseband calibration setup for ADC (b) Baseband calibration setup for DAC

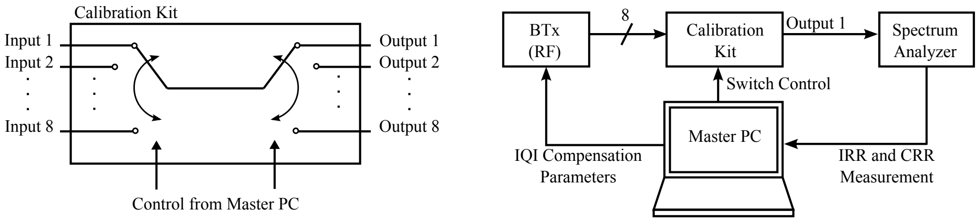
Figure 2: Setup of baseband calibration.

3.1 Baseband Calibration

The aim of baseband calibration is to reduce the timing skew between the baseband signals that output from the DACs or input into the ADCs. The timing skew between the ADCs or the DACs can be compensated by adjusting the programmable delay with precision of 10 ps. The setup of baseband calibration is as shown in Fig. 2, which is divided into ADC and DAC calibrations for the Rx and Tx, respectively. In Fig. 2(a), a sine wave reference signal generated by the signal generator is fed into the 48 ADCs by using the power splitter. As the phase imbalance of the splitter is very small (under 1 degree), the timing skew can be removed by adjusting the phase difference among the converted digital sine waveforms. In Fig. 2(a), the master PC firstly adjusts the phase difference among the reference ADCs of Rx boxes, then it adjusts the phase differences among the channels within the same BRx with respect to the reference ADC of this BRx. After the calibration of ADC, the BRx is used for DAC adjustment as a high precision oscilloscope. As shown in Fig. 2(b), the baseband outputs of the DACs are connected to the corresponding baseband inputs of the ADCs, where the DACs output sine wave signals with the same frequency. With measuring the phase differences among the sine waves, the delay for each DAC is adjusted. The processes can be automatic carried out by the control software at master PC.

3.2 Measurement of IQ Compensation Parameters

The developed channel sounder employs direct conversion architecture for the frequency up- and down-conversions. Due to the imbalances of the amplitudes and phases between the I and Q branches, it suffers from mirror image distortion. The principle of IQ imbalance compensation is developed in [4], and the process for the measurement of the IQ compensation parameters is as shown in Fig. 3(b), where a switch-based calibration kit is employed. The simplified structure of the calibration kit is shown in Fig. 3(a), that the input and output ports are selected with the switches controlled by the master PC. In Fig. 3(b), Complex exponential waves (25 MHz) are generated from the baseband IQ channels of the BTx, then master PC measures the image rejection ratio (IRR) and carrier rejection ratio (CRR) of each RF channel, by the spectrum analyser. When measuring the IQ compensation parameters of Rx channels, the BTx generates an IQ compensated 25 MHz complex exponential waves (with the parameters just measured) via RF circuit into the 8 × 8 switch unit and the signal is output to the selected Rx channel. The parameters can be calculated with the received baseband IQ signals. With this scheme, the process



(a) Structure of 8 × 8 switch unit (b) Measurement of Tx IQI parameters

Figure 3: Calibration kit and Tx IQI compensation parameters measurement.

also can be automatically performed.

3.3 B2B Calibration Measurement

For cancelling the frequency response of the baseband and RF circuits from the measured wireless channel transfer function, B2B calibration measurement is necessary. The B2B measurement is conducted by direct connection of Tx and Rx RF ports. However, when considering all possible MIMO combination of the Tx and Rx channels, it must take very long time. Although we have developed a switch unit (as shown in Fig. 3(a)) to automatically perform the B2B measurement for 8×8 MIMO connections one-by-one reducing manual operations, it still takes long time for the measurement. Here, we propose a *simplified B2B calibration measurement* for the fully parallel MIMO sounder, where we only measure the channel transfer functions of system $H^{\mathrm{sys}}_{m,1}(i)$, for $m = 1, \ldots, M$, and $H^{\mathrm{sys}}_{1,n}(i)$, for $n = 2, \ldots, N$, where $i = 1, \ldots, 2048$ is the index of the subcarriers of the multitone signal; m and n are the indices of the Rx and Tx channels; M and N are the numbers of the Rx and Tx channels, respectively. Then the interpolated channel transfer function of system of the combination of Tx and Rx channels is calculated as below.

$$\hat{H}^{\mathrm{sys}}_{m,n}(i) = \begin{cases} H^{\mathrm{sys}}_{m,n}(i) & \text{, for } m = 1 \text{ or } n = 1 \\ \frac{H^{\mathrm{sys}}_{m,1}(i) H^{\mathrm{sys}}_{1,n}(i)}{H^{\mathrm{sys}}_{1,1}(i)} & \text{, for } m \neq 1 \text{ and } n \neq 1 \end{cases}. \quad (1)$$

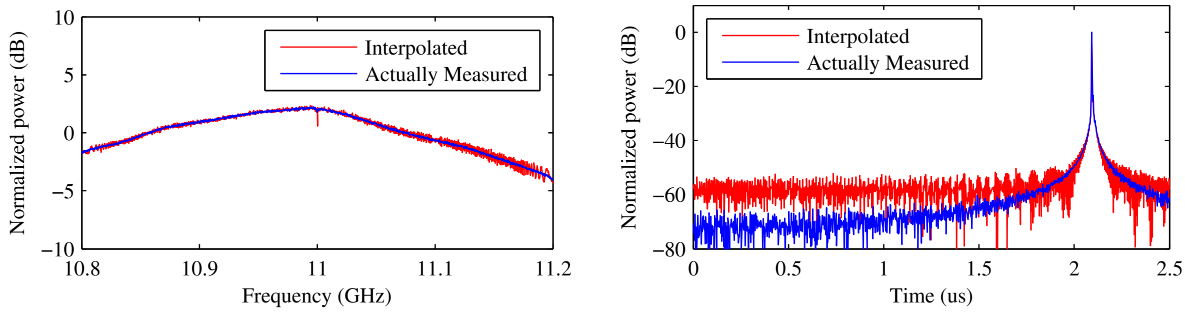
In this system, it is noted that the multitone signals are frequency-shifted for frequency division multiplexing (FDM) [2], that may cause some phase and amplitude error in (1). In simplified B2B calibration process, the measurement time can be greatly reduced from the order MN to the order $(M + N)$.

4. Verification of Simplified B2B Calibration

To verify the simplified B2B measurement, we measure a full $H^{\mathrm{sys}}_{m,n}(i)$, for $m = 1, \ldots, M$; $n = 1, \ldots, N$ and $i = 1, \ldots, 2048$; and compare the transfer function and impulse response of $H^{\mathrm{sys}}_{m,n}(i)$ (Actually Measured) with that of $\hat{H}^{\mathrm{sys}}_{m,n}(i)$ (Interpolated), for $m = 2, \ldots, M$ and $n = 2, \ldots, N$. Fig. 4 shows the results of Tx channel 8 to Rx channel 16 for example, and we can see that the error of transfer function is small and the shapes of the impulse responses are almost matching to each other. Although the degradation of the noise floor is about 10 dB, it is still small at about −60 dB. By the way, the root mean square error (RMSE) of the phase error is 0.0059 in radian, that is sufficiently small. We also measure a set of directly connected channels $H^{\mathrm{dir}}_{m,n}(i)$, that is essentially the same to $H^{\mathrm{sys}}_{m,n}(i)$. Fig. 5 shows the B2B calibrated results of $H^{\mathrm{dir}}_{m,n}(i)/H^{\mathrm{sys}}_{m,n}(i)$ (Actually Measured) and $H^{\mathrm{dir}}_{m,n}(i)/\hat{H}^{\mathrm{sys}}_{m,n}(i)$ (Interpolated). We can see both the transfer functions become flat, and both the peaks of the impulse responses are moved to time 0. However, the degradation of the noise floor is also about 10 dB.

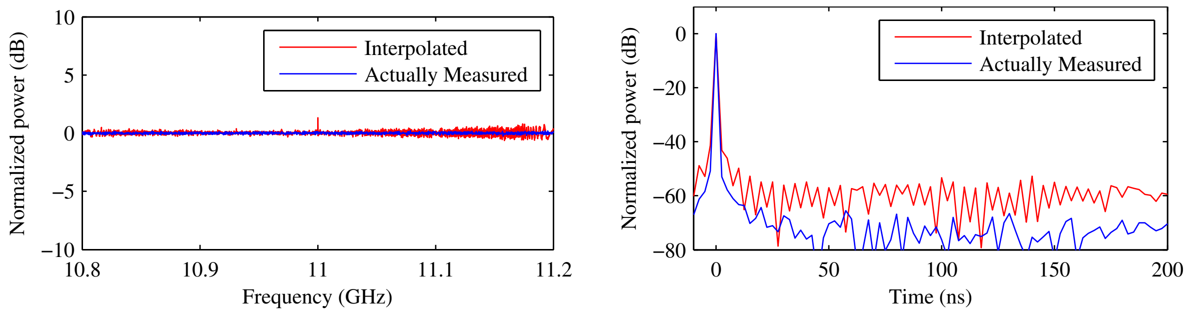
5. Conclusion

In this paper, the calibration techniques for the fully parallel MIMO sounder was introduced. A simplified B2B calibration measurement method was also proposed. With the automatic calibration processes and the simplified B2B measurement method, it is possible to shorten the time greatly for



(a) Transfer function (b) Impulse response

Figure 4: Comparison of the channel characteristic of the system (m = 16, n = 8).



(a) Transfer function (b) Impulse response

Figure 5: The B2B calibrated characteristic of the directly connected channel (m = 16, n = 8).

the calibrations, which provides a solution to the major drawback in a fully parallel architecture of the developed MIMO channel sounder.

Acknowledgments

This work was supported by "The research and development project for expansion of radio spectrum resources" of the Ministry of Internal Affairs and Communications, Japan.

References

[1] J. Gutiérrez, Ó. González, J. Pérez, D. Ramírez, L. Vielva, J. Ibáñez and I. Santamaría, "Frequency-Domain Methodology for Measuring MIMO Channels Using a Generic Test Bed," *IEEE Trans. Instrum. Meas.*, vol. 60, no. 3, pp. 827-38, Mar. 2011.

[2] Y. Konishi, M. Kim, M. Ghoraishi, J. Takada, S. Suyama and H. Suzuki, "Channel Sounding Technique using MIMO Software Radio Architecture," in *Proc. the 5th European Conference on Antennas and Propagation (EuCAP)*, Rome, Italy, Apr. 2011.

[3] B. T. Maharaj, J. W. Wallace, M. A. Jensen and L. P. Linde, "A Low-Cost Open-Hardware Wideband Multiple-Input-Multiple-Output (MIMO) Wireless Channel Sounder," *IEEE Trans. Antenna Propag.*, vol. 57, no. 10, pp. 2283-9, Oct. 2008.

[4] M. Kim, Y. Konishi, J. Takada, and B. Gao, "Automatic IQ Imbalance Compensation Technique for Quadrature Modulator by Single-tone Testing," *IEICE Trans. Commun.*, vol. E95-B, no. 5, May. 2012.