Simplified Multi-Channel Calibration for Microwave Imaging Systems

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***Abstract*—This work proposes and validates a simplified n-channel calibration for microwave imaging systems that reduces the complexity of a standard full-port calibration from a minimum of $4n-1$ measurements to $4(2)-1$ ones, respectively. The method consists of a joined 2-port standard calibration with a multi-port extrapolation. It compensates for systematic errors and mitigates the effects of losses and phase shifting caused by the multiplexing stage of a microwave imaging system. The conditioning and limitations of the technique are studied, including the switching matrix's dynamic range, insertion loss, and the error path extrapolation analysis. Finally, the calibration is validated by employing a brain stroke monitoring system using either an electromechanical switching matrix or a solid-state-based one, and repeatability and stability tests that demonstrate the calibration's effectiveness and robustness are performed.**

***Index Terms*—Calibration, biomedical microwave imaging, switching matrix**

I. Introduction

Microwave imaging (MWI) is a widely used non-ionizing, cost-effective, and non-invasive technology that exploits the penetrating ability of microwaves to retrieve dielectric contrast maps of an opaque domain of interest (DoI) via the solution of an ill-posed and non-linear problem. So, it has shown to be an attractive and advantageous alternative in biomedical applications, such as breast cancer and brain stroke imaging, where it is used for detecting, signaling, and following pathological-affected areas [1]. A typical MWI system comprises four main elements: first, a control unit, e.g., a laptop, controlling the data gathering and running the imaging algorithm. Second, a transceiver system that is in charge of generating the signals and recovering its back propagated response, i.e., collecting the scattering parameters. Third, the radiating elements, which are usually an array of n-antennas, surrounding the DoI, and fourth, a multiplexing stage, typically a switching matrix, connecting the transceiver with the radiating elements [2], [3]. This configuration enables multi-view schemes, which gather full scattering matrices needed for several imaging algorithms, thought the introduction phase shifting and path losses that should be calibrated.

The calibration aligns the measurement reference plane with the antenna's plane as commonly modeled and assumed by inversion imaging algorithms. It compensates for various sources of error, including the inherent cable imperfections, non-modeled switching matrices, and other components within the measurement set-up [4], [5]. So, a proper calibration ensures the scattering data correctly reflects the interaction between electromagnetic fields and the object under test, minimizing distortions and artifacts during the retrieval [6].

In an ideal scenario a full-port calibration is applied to the MWI system. However, the calibration becomes more challenging, complex, and time-consuming as the number of radiating elements, i.e., sensors/antennas, increases.

With this premise, we propose a method involving a joined two-step calibration process for multi-view configurations. Notably, this approach eliminates the need for a standard full-port $n \times n$ calibration, which requires at least $4n-1$ measurements, where n is the number of radiating elements [5]. Instead, this calibration method requires only $4(2)-1$ measurements. Then,

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the method is experimentally validated via an MWI system for brain stroke monitoring, using a Vector Network Analyzer (VNA) as the transceiver, a switching matrix, and twenty-two radiating antennas [3]. The experimental set-up consists of a mimicked hemorrhagic situation using a realistic phantom. The results demonstrate satisfactory retrieval performance.

II. Multi-Channel Calibration

To use this type of calibration, it is necessary (I) to verify the matrix's stability, ensure low losses, and confirm that the paths between the transceiver and the antennas are equivalent.

Then, the calibration is systematically implemented through a two-step process: (II) 2-port standard calibration, e.g., a short-open-load-thru (SOLT) calibration [5], followed by (III) a calibration extrapolation. Hence, the II-step assumes identical electrical paths and thus applies to a selected pair a 2-port standard calibration, extracting the respective calibration coefficients. This process includes measuring known reference standards at the antenna port, for instance, with an electronic calibration module (E-Cal) [7]. In the III step, the calibration coefficients obtained are then applied to all other pairs, i.e., extrapolating them.

III. Validation

To validate the calibration, we employ two versions of an MWI system for brain stroke monitoring, each differing in the switching matrix. One version uses electromechanical switches, and the other uses solid-state ones. The key difference lies in their physical mechanisms. The stability, repeatability, dynamic range, time switching, and insertion loss are verified for each matrix, with detailed performance comparisons in [8].

The I-step is performed for both the switching matrices. In the electromechanical case, all paths' electrical lengths are ensured, as they are designed and manufactured to the same physical length [3]. Instead, for the solid-state case, sixty-four antenna ports are available. Hence, we select twenty-two paths with identical electrical lengths. Second, a pair of paths is selected, and a standard 2-port calibration is performed, as described in II. Finally, the calibration coefficients are applied to all the other pairs, resulting in a fully calibrated 22×22 scattering matrix.

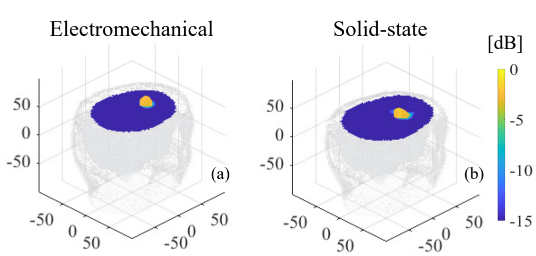

Fig. 1. 3-D normalized dielectric contrast sliced in the middle of the stroke region with (a) electromechanical and (b) solid-state switching matrix.

To verify the error introduced by applying the calibration from one path to another, different channels are examined under the same conditions by connecting an attenuator between two antenna ports, mimicking actual operating conditions in a more controlled scenario. A single path is calibrated, the device is connected to that path, and a measurement is taken. Then, the same calibration coefficients are applied to other paths where the attenuator is repositioned, and all measurements are taken. It is observed a maximum variation of approximately 0.2 dB in magnitude and 0.1 degrees in phase for both types of matrices. These results confirm the reliability and accuracy of the method.

Lastly, the procedure is also tested within an imaging retrieval of a hemorrhagic stroke condition, using the algorithm and system presented in [3]. The calibration is applied to compensate for the effects of switching matrix multiplexing from a two-pot VNA and twenty-two antennas surrounding a head phantom. Figure 1 shows the 3-D reconstructions of the normalized contrast, indicating a hemorrhagic stroke positioned at the front-right side (frontal lobe), approximately 5 cm from the top of the head.

IV. Conclusions

This work proposed and validated a joined two-step calibration method for multi-port MWI systems, which combines a 2-port standard calibration and a calibration extrapolation. It demonstrated its effectiveness, ensuring minimal variations in magnitude and phase across different matrix paths and non-disturbed imaging reconstruction. Accurate calibration is crucial for ensuring the reliability of measurements. Overall, this approach simplified the calibration process and decreased the time and complexity compared to a standard full-port calibration.

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