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Computational Millimetre-wave Imaging Based on Single Electric-Field Scan

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Abstract—A scheme for reducing the need of multi-scan measurements of near electric-field information to a single-scan process is presented to simplify the construction of the sensing matrix required for performing computational mmWave imaging system at K-band frequencies. For this purpose, we propose to perform only a single scan, and the obtained information is used to construct the multiple radiated near electric-field information associated to all transmit and receive units. Further, the performance of the constructed near electric-field is verified by generating an image of a test target by means of computational imaging using the scene reflectivity information. The proposed scheme helps in reducing the overall complexity of the nearfield scanning process associated to the computational imaging system.

Keywords—Computational imaging, electric field pattern, near-field, millimetre-wave, scan, WR42.

I. INTRODUCTION

Electromagnetic (EM) computational imaging systems have seen a tremendous success for a wide range of applications related to security, smart health care, wireless sensing, and many more [1, 2]. In computational imaging [3], [4], the scene is illuminated with radio waves, some of which are backscattered and measured by the system. This measurement data is then used to reconstruct an image of the scene. The measurement process is a linear mapping of the scene via a sensing matrix into the measured data. The sensing matrix contains the measurement modes that probe the scene and multiplex the scene information. The probing of the scene through the sensing matrix involves several measurements of the near electric-field patterns (NEP) which represent the measurement masks.

In this paper, a two-dimensional (2D) computational millimetre-wave (mmWave) imaging system with a single near electric-field scan of the transmitter/receiver antenna is presented. For simplicity, we consider an open-ended waveguide probe (WR42) [5] as transmitter as well as receiver antennas. First, the near electric-field of one of the WR42 probes is measured over a 2 GHz bandwidth at a centre frequency of 21 GHz. Based on this single-scan near electric-field information, the electric-field aperture is constructed for each transmitter and receiver antennas. Next, each constructed electric field is used to build the sensing matrix for further imaging process.

This work demonstrates a computational concept using electric-field information from a single-scan without the need for a priori knowledge of all near electric-field patterns. The proposed approach reduces the complexity of NEPs measurements as the same measured electric-field is utilized to construct the sensing matrix associated with all measurement modes. This paper uses a fixed number of probes to represent all measurement masks. Each measurement mode is represented by the NEP created by each transmitter-receiver arrangement. The major contribution of [3], [6] is the compressive computation by utilizing a single radio channel. However, the accurate characterization of all NEPs that represent all considered masks is still required. Therefore, this paper mainly focuses on reducing the number of required NEP scans to one. This way the complexity related to the computational imaging will be further simplified.

The rest of the paper has been organized as follows. In Section II, we present the computational imaging model and formulate the imaging problem. Section III discusses the proposed method to construct the sensing matrix from a single electric-field scan. Finally, Section IV presents our simulated results, and the conclusions are drawn in Section V.

II. COMPUTATIONAL MMWAVE IMAGING

A. Theory of Computational Imaging

The computational imaging process was outlined in detail in [4], [7] and is illustrated in Fig. 1. The near field scan aperture is located at 5λ (free space wavelength at 21 GHz) from the transmit (Tx) and receive (Rx) antenna aperture plane, and the scene is at 2λ from the near field plane.

The computational imaging involves two main measurement steps: first, the measurement of NEPs and then, the measurement of the signals backscattered by the scene for all considered masks. For NEP measurement, the first-Born approximation is considered to construct the sensing matrix of a transceiver channel. The sensing matrix is constructed by a linear combination of the electric fields, \( \mathbf{E}_{Tx} \) and \( \mathbf{E}_{Rx} \). Here, \( \mathbf{E}_{Tx} \) and \( \mathbf{E}_{Rx} \) denote the radiated and received electric fields, respectively, for the considered transmitter-receiver mask. Next, the second step requires the measurement of all backscattered signals related to each mask. The latter are linked to the scene reflectivity, \( f \), through
the sensing matrix, and it can be mathematically represented as,

\[ g_{M \times 1} = H_{M \times N} f_{N \times 1} + n_{M \times 1}, \]  

(1)

where, \( g \) is the measured backscattered radio signals, \( H \) is the sensing matrix, and \( n \) is the measurement noise. Finally, the scene reflectivity, \( f \), can be estimated by means of any known computational reconstruction algorithm, such as matched-filter or least-squares. In (1), \( M \) denotes the number of total considered masks associated by the Tx-and-Rx pairs to sample the scene information, whereas \( N \) is the number of pixels used to represent the imaged scene. In this work, the matched-filter technique is used for image reconstruction. Using matched filtering, the imaged scene can be reconstructed as:

\[ f_{\text{est}} = H^\dagger g, \]  

(2)

where the symbol \( ^\dagger \) denotes the Hermitian transpose operator.

B. Transmit and Receive Aperture plane

The transceiver aperture plane is illustrated in Fig. 2.

It consists of 17 transmit (Tx) antennas and 40 receive (Rx) antennas. The number of considered antennas is related to the masks according to (1), and hence the quality of imaged scene increases with the masks. In this study, we have randomly considered 17-Tx and 40-Rx antennas for demonstrating the concept of single-scan process. Here, the WR42 probe is considered as the Tx and Rx antenna. The distance between two consecutive probes is \( 0.84\lambda \). This forms a square plane where Tx antennas are positioned in the middle whereas Rx antennas are at the edges. The probe is modelled using the full-wave EM CST studio platform. In Fig. 3 the \( S_{11} \) for one single probe antenna, as well as the coupling between consecutive transmitters as a function of the separation between them, is shown. In particular, separations of \( 0.84\lambda, 1.68\lambda, \) and \( 2.52\lambda \) were considered.

The \( S_{11} \) curve is around \(-10 \, \text{dB}\) over the \( 20 \text{–} 22 \, \text{GHz} \) frequency band whereas the coupling between two successive Tx probes is lower than \(-25 \, \text{dB} \).
over the same plane varies because of the different relative positions of Tx and Rx with respect to the near field aperture. This means that the ‘projected-radiated NEPs’ by the central probe (Tx) are different compared to any other Rx probe positioned at the edge. This can be further generalized for all probes as their relative positions are different to the near field aperture. Because of this, these ‘projected-radiated NEPs’ are always different. Hence the $M$ measurements mode assumption remains valid.

Moreover, if we shift the considered area diagonally by a length $\sqrt{2}d$ (for the definition of $d$, see Fig. 4), then the projected NEPs on this plane (depicted in Fig. 4 with a dashed brown boundary) by the central probe corresponds to the projected fields due to the probe marked with a star as when the plane is not shifted. In other words, we can assert that the ‘projected-radiated NEPs’ due to the central probe over an extended length ‘$d$’ (as shown with the blue coloured area in Fig. 4) can be assumed as a superset and the intended area is an intersection of all subsets (projected fields due to all probes). The extended length $d$ can be determined as the distance between the central Tx-probe and the Rx-probe at the edge (see Fig. 2). This can also be generalized for any other squared transceiver structure such as that shown in Fig. 2.

As previously discussed, the projected fields are calculated for two different positions, which are presented in Figs. 5 and 6. The considered Tx and Rx positions for these analyses are highlighted with blue and red colours in Fig. 2.

The peak of $|E_{x}|$ and $|E_{y}|$ components are located at the considered Tx-probe position. Likewise, the peak of Rx-probe is seen in Fig. 6 at the position of the considered Rx-probe. Next, the projected near fields are used to construct the sensing matrix, $\mathbf{H}$, and then used for computational imaging according to (2).

IV. IMAGING RESULT

For this study, we collect the simulated $g$ signals as backscattered measurements ($S_{21}$) from the full-wave simulations in CST Microwave Studio. The collected backscattered signals for one cross-shaped object are presented in Fig. 7.

The cross-shaped object consists of two metal strips perpendicular to each other as depicted as inset in Fig. 7. The dimensions of the object are selected in accordance with the image resolution limit of 5 mm according to [8], [9].

A total of 680 backscattered measurements over a 2 GHz bandwidth (20-22 GHz) is used for image reconstruction. The measurement information is collected in two steps. First, the $S_{21}$ (backscattered signals) are collected in the presence of an object and second, in its absence, to resemble the background information. This way, the unwanted noisy signals originating from the background are removed from the main backscattered signals.
information. Based on the explained single-scan scheme, the reconstructed image is presented in Fig. 8. The reconstructed image clearly resembles the shape of the object considered for study. Moreover, the quality of the reconstructed image is proportional to the number of measurement modes, which means that it can be improved with more measurements. Consequently, the difficulties related to the scanning of near electric-field patterns become more prominent. However, the presented single-scan scheme provides a good way to resolve such complexity.

V. CONCLUSION

In this paper, we presented a single-scan scheme to achieve a computational mmWave imaging over the 20-22 GHz, K-band frequency. This scheme processes the single-scanned near electric-field patterns information for the construction of sensing matrix, eliminating the need for multiple scans to sample the scene information. The single-scan concept achieves this by utilizing the selected projected near electric-field patterns from a larger aperture of the near electric-field pattern.

We demonstrated that the constructed near field information from the projected near electric-field patterns has a good performance for the reconstruction of the mmWave image. Usually, the sensing matrix is constructed from measurements gathered during multiple scans, which is a repetitive as well as a tedious task. Hence the presented single-scan scheme reduces the overall measurement complexity of the mmWave computational imaging system. The obtained full-wave results confirm the feasibility of such scheme to facilitate the computational imaging, and potentially, other applications involving imaging through construction of sensing matrix by multi-scan process.

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