Environment Mapping with 28 GHz Beam Steering Transceivers Using the SAGE Algorithm: Preliminary Results

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***Abstract*—This paper presents a multipath component (MPC) parameter estimator for indoor environment mapping that uses the 28 GHz radio band. It employs a commercial-off-the-shelf (COTS) radio frequency transceiver chipset capable of beam steering within an azimuth angle range of -78^o and $+78^o$ but with only a single RF chain. Existing space-alternating generalized expectation-maximization (SAGE) algorithms for MPC parameter estimation are designed specifically for multi-antenna systems, with each antenna having its own baseband representation. By exploiting the beam steering characteristics, we adapted the SAGE algorithm to make it suitable for analyzing a single-baseband based multi-antenna array system. The anechoic chamber measured array radiation pattern for each steering direction is used in our algorithm to determine the MPC contribution. In an office setting, the transmitter and receiver antenna beams are swept. All backscatter responses are collected for all possible pairs of transmitter/receiver steering angles, and an angular map that contains the power profile is produced. The performance of the proposed algorithm is validated by simulation and measurement data.**

***Index Terms*—Environment mapping, MPC, baseband, SAGE, beam steering, multi-antenna array.**

I. Introduction

The emergence of millimeter-wave (mmWave) technology has enabled a range of new applications in wireless communications, such as gigabit-per-second data rates and ultra-low-latency links. However, the potential of mmWave is not limited to just communication applications. Due to their distinctive characteristics, such as high directionality, large bandwidths, and inability to penetrate obstacles, mmWave signals also provide interesting possibilities for sensing [1]. The high attenuation of the mmWave signal can be compensated using beamforming. Beam steering, which uses a phased antenna array to focus and direct a beam in a specific direction, has recently gained popularity because it adds scanning capability to mmWave-based sensing applications [2].

This has led to increasing interest in the use of mmWave for integrated sensing and communication (ISAC) purposes. ISAC is a new research area that aims to utilize the same transmit waveforms and processing modules for both wireless communication and radar sensing within a single system [3] [4]. The primary difference between using a mmWave system and a radar system for sensing is that a radar system has multiple radio-frequency (RF) chains and analog-to-digital converters (ADCs), which enables signal processing in the digital baseband domain, and it sends predefined waveforms. The wideband and narrow beam waveforms existing in mmWave-based ISACs turned to high-resolution sensing applications [5]. However, these waveforms are not optimized for sensing purposes as they are in typical radar systems. Such system requires a robust and computationally efficient signal processing algorithm for the extraction of MPC parameters from the received data of a noisy environment.

A variety of algorithms exist for Multipatch Component (MPC) estimation in wireless channels. These algorithms can be divided into three categories: spectral estimation, subspace-based techniques and maximum likelihood techniques. Multiple signal classification (MUSIC) and estimation of signal parameters via rotational invariance technique (ESPRIT) algorithms are representatives of the first two categories, and Space Alternating Generalized Expectation-Maximization (SAGE) and RIMAX algorithms are representatives of the third [6]–[8]. Existing algorithms, on the other hand, are designed for multi-antenna systems, in which each antenna has its own RF chain and baseband representation.

In this paper, we adapt the SAGE algorithm for MPC parameter estimation by utilizing all joint beam steering directions of the receiver and the transmitter, which differs from conventional channel parameter estimation that utilizes received baseband data for each antenna. When using a 28 GHz beam steering multi-antenna array, there are

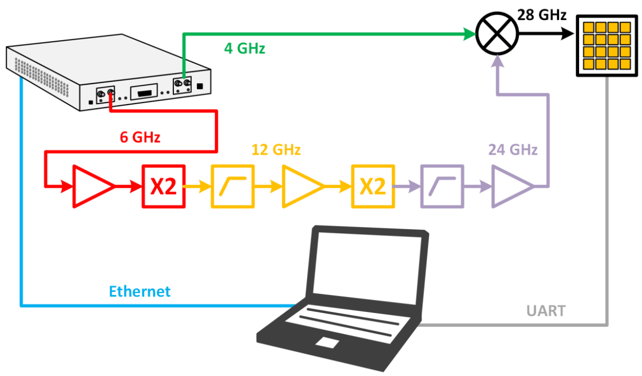

Fig. 1. Block-diagram of the 28 GHz transmitter.

two challenges to MPC identification. The first is that the wide beamwidth of the array's radiation pattern can conceal smaller MPCs. The second is the presence of high-power side lobes, which makes it challenging to determine MPC contributions. The performance of the proposed algorithm is demonstrated by utilizing the measured power profile in a typical office environment. In particular, because the proposed approach aims to map the indoor environment using MPC parameter estimation, we show promising results in reproducing scatterer angular information.

The original contributions of this study are summarized as follows:

- This study develops a signal model for phased antenna array-based beam steering for directional scanning; in addition, the formulation and implementation of the adapted SAGE algorithm are presented;
- The channel measurement results from an indoor office environment at a mmWave band of 28 GHz are presented and the angular information of all corresponding scattering devices is extracted from MPCs.

The rest of the paper is organized as follows. Section II presents the signal model. Section III reports the description of the proposed algorithm, while Section IV discusses the performed measurement campaign, and the results are reported. Finally, Section V draws the conclusions.

Notations: in this paper, $(\cdot)^T$ denotes the transpose, $|\cdot|$ represents the amplitude, bold capital letters (e.g. $\mathbf{X}$) represent matrices, bold lower-case letters (e.g. $\mathbf{f}$) represent vectors, and non-bold letters represent scalars.

II. Signal Model

In this section, we will consider the signal model when a mmWave system is used with only a single baseband chain, and a digitally-controlled phased array that can form a beam in a direction θ_m. Such an architecture is shown for a transmitter in Figure 1 (this architecture will be detailed in Section IV).

Let us assume that the phased array, when steering in direction θ_m, has a radiation pattern $f(\theta_l, \theta_m)$ where θ_l is the direction in which the radiation pattern is measured.

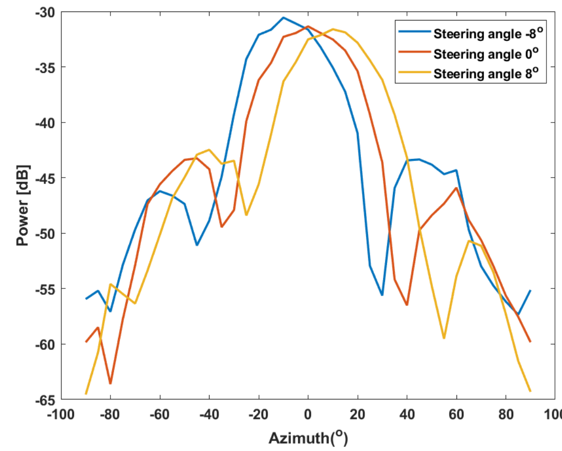

Fig. 2. Radiation patterns of the proposed antenna array at different angles

Figure 2 shows such a measured radiation pattern for an antenna array for different steering directions (the details of the experimental setup will be given in Section IV).

If the transmitter sends a signal $x(t)$ when the transmitter is steering in direction θ_m, the signal sent in direction θ_l is given by

$$x(\theta_l, \theta_m, t) = f(\theta_l, \theta_m) \cdot x(t) \tag{1}$$

Let us assume that the transmitter and receiver both have the same architecture (a single baseband chain with a digitally-controlled phased array) and an identical radiation pattern $f(\theta_l, \theta_m)$ when steering in direction θ_m. The channel is considered to be a multipath channel with L propagation paths that have complex amplitudes α_l, departure angles θ_l^{Tx} and arrival angles θ_l^{Rx}, with $l = 1, ..., L$. When the transmitter is steering in direction θ_m^{Tx} and the receiver is steering in direction θ_m^{Rx}, the received signal is given by:

$$y(\theta_m^{Rx}, \theta_m^{Tx}, t) = x(t) \cdot \sum_{l=1}^{L} \alpha_l f(\theta_l^{Rx}, \theta_m^{Rx}) f(\theta_l^{Tx}, \theta_m^{Tx}) + n(t) \tag{2}$$

where $n(t)$ represent the i.i.d. Gaussian noise. Note that (2) does not consider the propagation delay, but rather a narrowband channel (or a single carrier in a multicarrier system). In the previous development, we also assume that all propagation is done in the azimuth plane and ignore elevation.

Let us call $Y(\theta_m^{Rx}, \theta_m^{Tx})$ the complex amplitude of a single received packet (when the receiver steers in direction θ_m^{Rx} and the transmitter steers in direction θ_m^{Tx}). When both transmitter and receiver steer in all possible directions, the collected complex amplitudes will create a 2-D matrix $\mathbf{Y}$ that should show peaks at the angles of the MPCs $(\theta_l^{Rx}, \theta_l^{Tx})$. The size of $\mathbf{Y}$ is $K^{Rx} \times K^{Tx}$, where K^{Rx} and K^{Tx} represent the number of steering directions for the receiver and the transmitter, respectively.

Such a 2-D map is shown in the experimental result in Figure 4, where the colormap represents the power spectrum as a function of transmit and receive steering angle. In this figure, the Line-of-sight can be clearly be observed at $(\theta_l^{Rx}, \theta_l^{Tx}) = (0°, 0°)$. The contribution of the reflected paths (at $(\theta_l^{Rx}, \theta_l^{Tx}) = (30°, -30°)$ and $(\theta_l^{Rx}, \theta_l^{Tx}) = (-30°, 30°)$) can also be observed, but are more difficult to distinguish from the sidelobes of the antenna array (for example at $(\theta_l^{Rx}, \theta_l^{Tx}) = (0°, 60°)$). The SAGE algorithm presented in the next section allows us to identify the contributions of the MPCs without ambiguity by exploiting knowledge of the radiation pattern.

Based on (2), the signal model for the contribution of a single MPC to $\mathbf{Y}$ is given by:

$$\mathbf{S}_l = \alpha_l \cdot \mathbf{f}^T(\theta_l^{Rx}) \cdot \mathbf{f}(\theta_l^{Tx}) \tag{3}$$

where $\mathbf{f}(\theta_l^{Rx})$ is a $1 \times K^{Rx}$ vector containing the value of the radiation pattern of the receiver in direction θ_l^{Rx} for all receiver steering directions θ_m^{Rx}. Similarly, $\mathbf{f}(\theta_l^{Tx})$ is a $1 \times K^{Tx}$ vector containing the value of the radiation pattern of the transmitter in direction θ_l^{Tx} for all transmitter steering directions θ_m^{Tx}. By considering (2) and (3), it can be observed that

$$\mathbf{Y} = \sum_{l=1}^{L} \mathbf{S}_l + \mathbf{N} \tag{4}$$

where $\mathbf{N}$ is a $K^{Rx} \times K^{Tx}$ noise matrix containing i.i.d. Gaussian elements, representing the noise on the complex amplitude for each transmiter and receiver steering direction.

III. Algorithm

The SAGE algorithm is a popular method for multipath parameter estimation in wireless communication systems, which can take into account calibration and antenna pattern characteristics. It is a maximum-likelihood estimator that uses an iterative approach to estimate the multipath parameters from the received signal [9], [10]. It has been extensively researched in the literature in a variety of scenarios, including indoor and outdoor environments, as well as various wireless communication standards such as Wi-Fi, cellular, and satellite communication [9].

One of the main problems of using beam steering arrays for environment mapping is the presence of high sidelobes in the antenna array, as shown in Figure 4. While strong contributions (such as the Line-of-sight) can easily be identified, it is more difficult to distinguish whether smaller contributions are multipath components or contributions from the sidelobes of the antenna array.

The SAGE algorithm relies on iterative Expectation-Maximization (EM) steps. The observable data of the l^{th} MPC is computed using the first estimates of the $L-1$ MPCs in the expectation step. This step consists of removing the first $L-1$ estimated MPCs from the measured channel matrix. If the first $L-1$ MPC estimates are reliable, there will only be the l^{th} MPC's contribution left. The spatial parameters (angular and temporal) of the l^{th} MPC are then updated in the maximization step, alongside its estimated amplitude. The algorithm converges when the variance in the parameter estimates between two subsequent iterations falls below a predetermined threshold. It should be noted that the initialization step is crucial in the SAGE algorithm to guarantee that the algorithm converges to the global optimum (rather than a local one).

The main difference of the algorithm used in this paper concerns the signal model: instead of having received baseband data for each antenna (as is the case in classical MIMO channel estimation), our algorithm exploits the received baseband data for each steering direction of the Tx and Rx arrays' beam. This requires careful measurement of the array's radiation pattern (for each steering direction) but allows our algorithm to distinguish contributions of MPCs from contributions due to sidelobes of the antenna array.

A. Expectation-Maximization algorithm

The expectation and maximization step are repeated iteratively for each MPC l, for a certain number of iterations. In these two steps, the observable data for each path, along with their angular parameters, are estimated until they converge using the threshold method.

Expectation step: In this step, the estimation of the observable data of the l^{th} path is performed by removing $L-1$ path contributions (i.e. the most recent MPC estimates), as shown in the following equation:

$$\hat{\mathbf{X}}_l^{(i)} = \mathbf{Y} - \sum_{l'=1, l' \neq l}^{L} \mathbf{S}_{l'}^{(i)} \tag{5}$$

where $\mathbf{Y}$ is the 2-D matrix containing all measured complex received amplitudes (for all transmit and receive steering directions), and $\mathbf{S}_{l'}^{(i)}$ is the signal model defined in (3) for MPC l' at the i-th iteration.

Maximization step: in this stage, all the parameters of MPC l are updated (from iteration i to iteration $i+1$) as follows:

$$(\hat{\theta}_l^{Rx(i+1)}, \hat{\theta}_l^{Tx(i+1)}) = \underset{(\theta_m^{Rx}, \theta_m^{Tx})}{\operatorname{argmax}} (|\hat{\mathbf{X}}_l^{(i)}|) \tag{6}$$

where the search is performed over all elements of $\hat{\mathbf{X}}_l^{(i)}$, i.e. overall steering directions of the transmitter and receiver array. In other words, since $\hat{\mathbf{X}}_l^{(i)}$ is supposed to contain only the contribution of the l-th path (if the expectation step was effective), the indexes of the maximum in the power spectrum indicate the directions of the l-th MPC.

The complex amplitude $\alpha_l^{(i+1)}$ is updated as follows:

$$\alpha_l^{(i+1)} = \hat{\mathbf{X}}_l^{(i)}(\hat{\theta}_l^{Rx(i+1)}, \hat{\theta}_l^{Tx(i+1)}) \tag{7}$$

In other words, the complex amplitude of path l is that of $\hat{\mathbf{X}}_l^{(i)}$ at the maximum value in it's power spectrum.

B. Initialization stage

As mentioned previously, it is important to properly initialize the parameters $(\alpha_l^{(0)}, \theta_l^{Rx(0)}, \theta_l^{Tx(0)})$ for $l = 1, ..., L$ for the SAGE algorithm to converge to the global optimum.

During the initialization step, each individual path's parameters are initialized by successive path cancellation from the received signal strength matrix $\mathbf{Y}$. First, the residual measurement for the previously estimated paths is computed:

$$\mathbf{Y}_{res,l} = \mathbf{Y} - \sum_{l'=1}^{l-1} \mathbf{S}(l') \tag{8}$$

Then, the parameters of the l^{th} path are estimated from the residual measurement:

$$(\hat{\theta}_l^{Rx(0)}, \hat{\theta}_l^{Tx(0)}) = \underset{(\theta_m^{Rx}, \theta_m^{Tx})}{\text{argmax}} \left(|\mathbf{Y}_{res,l}| \right) \tag{9}$$

Similarly, the complex amplitude is estimated as follows:

$$\alpha_l^{(0)} = \mathbf{Y}_{res,l}(\hat{\theta}_l^{Rx(0)}, \hat{\theta}_l^{Tx(0)}) \tag{10}$$

Such an initialization relies on the fact that the highest peak in the power spectrum of the (residual) measurement must indicate the presence of an MPC.

IV. Experimental Setup and Results

A. Experimental setup

The software defined radios (SDRs), up- and down- converter, and multi-antenna arrays are the three different components used to realize the 28 GHz SDRs-based transceiver system. The SDRs are used to process signals at sub-6 GHz (i.e. to generate the baseband and intermediate frequency signals). The up- and down-conversion components are used to convert the signal to 28 GHz and to sub-6GHz, respectively. An antenna array receives the upconverted 28 GHz RF signal for transmission, with a digital control port controlling the beam direction. Figure 1 depicts the block diagram of the proposed 28 GHz transmitter; the receiver has a very similar block diagram.

We employ a phased array antenna system to generate and steer beams towards different directions in the indoor environment. Figure 2 shows the proposed antenna array radiation patterns at given steering angles. It is demonstrated that the maximal directions of the patterns change depending on the beam steering angles. The received signal strength information at various points in the environment is collected and processed using the SAGE algorithm to estimate the angular information of the MPCs. Figure 3 depicts the environmental setup.

B. Results

The matrix of measured complex amplitudes $\mathbf{Y}$ measured in the environment was fed into the SAGE algorithm to obtain parameter estimates for a given number of paths. The antenna radiation pattern of the antenna array was measured in an anechoic chamber (for each steering direction) to obtain the vector $\mathbf{f}(\theta_l)$ for all values of θ_l.

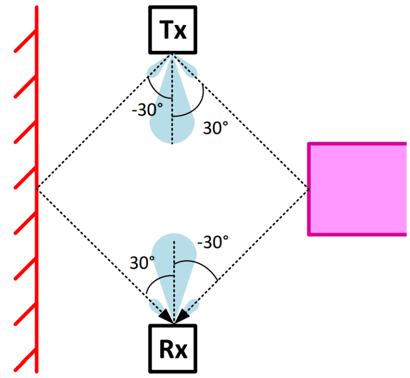

Fig. 3. Scenario of the measurements.

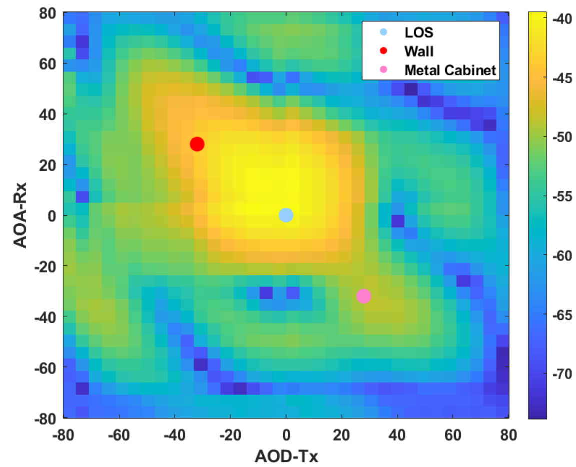

Fig. 4. Power spectrum as a function of transmitter and receiver steering angle. The MPCs estimated with SAGE are superimposed to the power spectrum, and identified as the LOS, wall reflection, and metal cabinet reflection.

The power spectrum of the measured data is shown in Figure 4. It can be seen that the power associated with MPCs and the sidelobes associated with the LoS path are in the same order of magnitude, highlighting the necessity of using an algorithm that is able to include the effect of the radiation pattern.

The proposed SAGE algorithm extracts angular information successfully, as shown in Figure 4 for the scenario depicted in Figure 3. From the figure, the estimated MPCs are pointed by colored circular circles. The LoS path has a power 5 dB higher than non-LoS (NLoS) paths and contributes significantly to 28 GHz wave propagation in an indoor environment. The second most powerful MPC is the wall reflection, The metal cabinet reflection has the lowest power. Although there are a limited number of MPCs in this experiment, the proposed algorithm produces a promising result; however, as the number of paths increases, more parameters are required to distinguish between the various paths.

V. Conclusion

In this paper, we use the SAGE algorithm to perform a preliminary identification of MPC contributions. A 28 GHz beam steering transceiver architecture based on SDRs with 4X4 antenna arrays was presented. The suggested SAGE algorithm utilizes the provided multi-antenna array radiation pattern for each steering direction to distinguish the MPC contribution. In an indoor setting, a preliminary measurement campaign was carried out. The walls and metal cabinets within the indoor environment are then located using the estimated angular information. After analyzing the experiment results, we concluded that the proposed SAGE algorithm can provide accurate estimates for nearly all MPCs if the channel contains only a few MPCs and experiences moderate power decay.

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References

[1] M. Passoja, “5G NR: Massive MIMO and Beamforming–What Does It Mean and How Can I Measure It in the Field,”, 2018.

[2] Carlos Baquero Barneto, Elizaveta Rastorgueva-Foi, Musa Furkan Keskin, Taneli Riihonen, Matias Turunen, Jukka Talvitie, Henk Wymeersch, Mikko Valkama, ”Millimeter-wave Mobile Sensing and Environment Mapping: Models, Algorithms and Validation”, IEEE Transactions on Vehicular Technology, 2022.

[3] Yi Zhong, Tianqi Bi, Ju Wang, Jie Zeng, Yan Huang, Ting Jiang, Qiang Wu, Siliang Wu: ”Empowering the V2X Network by Integrated Sensing and Communications: Background, Design, Advances, and Opportunities.” IEEE Netw. 36(4): 54-60 (2022).

[4] Emanuele Grossi, Marco Lops, Antonia Maria Tulino, and Luca Venturino. 2021. ”Opportunistic Sensing Using mmWave Communication Signals: A Subspace Approach.” IEEE Trans. Wirel. Commun. 20, 7 (2021), 4420–4434, (2021).

[5] M. A. Islam, G. C. Alexandropoulos and B. Smida, ”Integrated Sensing and Communication with Millimeter Wave Full Duplex Hybrid Beamforming,” ICC 2022 - IEEE International Conference on Communications, Seoul, Korea, Republic of, (2022).

[6] B. H. Fleury, M. Tschudin, R. Heddergott, D. Dahlhaus, and K. I. Pedersen, ”Channel parameter estimation in mobile radio environments using the SAGE algorithm,” IEEE J. Sel. Areas Commun., vol. 17, no. 3, pp. 434–450, Mar. (1999).

[7] Feng R, Huang J, Sun J, et al. A novel 3D frequency domain SAGE algorithm with applications to parameter estimation in mmWave massive MIMO indoor channels. Sci China Inf Sci, 2017, 60(8): 080305, doi: 10.1007/s11432-017-9139-4

[8] D.P. Gaillot, E. Tanghe, P. Stefanut, W. Joseph, M. Lienard, et al.. ”Accuracy of specular path estimates with ESPRIT and RiMAX in the presence of diffuse multipath.” 12th COST 2100 Management Committee Meeting, 2010, Bologna, Italy. ⟨hal-00574430⟩.

[9] A. Richter, “Estimation of radio channel parameters: models and algorithms”, Thesis, TU Iimenau, (2005).

[10] X. Yin, C. Ling, and M.-D. Kim, ”Experimental multipath-cluster characteristics of 28-GHz propagation channel,” IEEE Access, vol. 3, pp. 3138–3150, (2015).