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Fast Array Diagnosis Based on Measured Complex Array Signals with Short Measurement Distance

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***Abstract*—Fast array diagnosis method is of great importance for ensuring reliable array performances in the fifth generation (5G) communication systems. In this paper, a fast array diagnosis method is presented for antenna arrays composed of several subarrays. The objective is to detect the failures based on the measured complex array signals in short measurement distance. A single probe is required to record the array response in the near-field of the array. All the array elements are excited simultaneously, and only phase shift states of 0° and 180° are required in the measurements. For a base station (BS) antenna array with N subarrays, $N+1$ measurements are required, resulting in a fast diagnosis process. Finally, the proposed method was validated in an antenna array composed of 4 subarrays with 3 antenna elements in each subarray and successful diagnosis results (both for the whole subarray and single antenna element failure cases) can be observed.**

***Index Terms*—array diagnosis, antenna measurement, base station antennas, complex signal measurement.**

I. Introduction

Multi-element antenna array is extensively utilized in the fifth generation (5G) systems [1], [2]. Typically, the array elements are divided into subarrays in the 5G base station (BS), where linear progressing phase can be assigned to different subarrays to achieve beamforming capability. The increasing number of antenna elements employed in the BS makes the detection of array failure a more pronounced issue. Besides, the failures can be caused by the damaged cables, loosened connection etc. Thus, it is also of importance to identify whether the disconnection occurs at the antenna feed or the subarray feed.

Faulty antenna elements can be easily detected when the excitation of each antenna element can be obtained. For large arrays, the far-field condition is difficult to fulfil in reality, making far-field region diagnosis methods extremely expensive and unpractical. The traditional field transformation methods [3]–[5] can be applied to diagnose the faulty elements via reconstructing the aperture field distribution based on near-field samples. However, a large number of samples are required. Matrix methods were developed to detect failing elements based on stadard linear algebra operateors [6] or the Moore-Penrose matrix pseudoinversion [7]. Nevertheless, the required measurements are significantly larger than the number of array elements. It is time-consuming to do the near-field scanning for both the field reconstruction and matrix methods. Array diagnosis using sparse source reconstruction [8]–[10] was proposed to reduce the number of near-field samples and thus shorten the scanning time. The drawback is that the pre-knowledge of a faulty-free array is required, which may not be available in some situations. In [11] and [12], array calibration was achieved by solving linear equations based on several different phase settings of array elements and the corresponding measured field samples. The array elements are properly excited and measured simultaneously with only a small number of measurements required. This method is attractive since it is fast and can be conducted in near-field for array diagnosis purpose with higher tolerance in estimation errors.

In [11], the phase setting matrix is generated using a recursive matrix-forming method based on Hadamard matrix and other basic matrices. A simpler phase setting matrix design introducing 180° phase shift into one subarray in turns is proposed in this paper. The detection is achieved by solving linear equations based on the measured complex array signals. The faulty type can be identified by comparing the estimated excitation amplitude of the failure subarray with the amplitude of normal subarrays. The proposed method is discussed in Section II , and the experimental results are shown in Section III. Finally, conclusion and future work are provided in Section IV.

II. Theory

A. Signal Model

The multi-element array diagnosis system is illustrated in Fig. 1. The device under test (DUT) contains N subarrays and each subarray includes P antenna elements. The proposed method requires phase shifters to tune the phase of each subarray between 0° and 180°. A single probe is employed to receive the complex array signals. It is located in the boresight direction of the DUT within its near-field range. The discussion is limited to a single polarized antenna array, however, the extension of the dual-polarized case is straight-forward. The signal model of the diagnosis system can be expressed as:

$$\mathbf{\Psi} \cdot \mathbf{x} = \mathbf{b}, \tag{1}$$

$$\mathbf{\Psi} = \begin{bmatrix} e^{j\phi_{1,1}} & \dots & e^{j\phi_{N,1}} \\ \vdots & \ddots & \vdots \\ e^{j\phi_{1,M}} & \dots & e^{j\phi_{M,N}} \end{bmatrix} \tag{2}$$

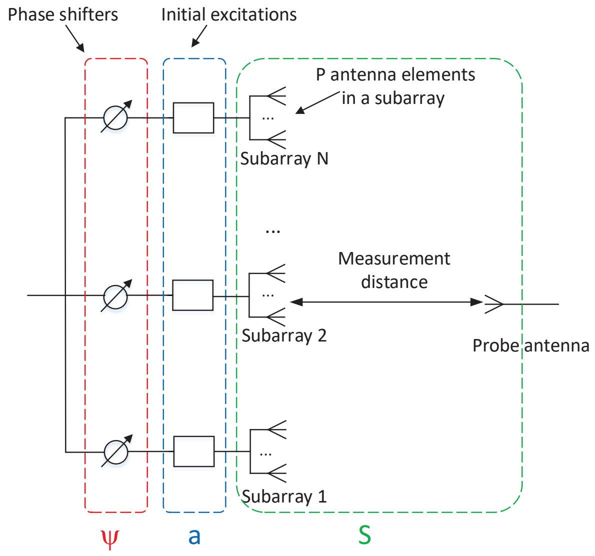


Fig. 1. The schematic of multi-element antenna array diagnosis system.

$$\mathbf{x} = [a_1 S_1 \ \ldots \ a_N S_N]^T \tag{3}$$

$$\mathbf{b} = [b_1 \ \ldots \ b_M]^T \tag{4}$$

where the matrices $\Psi \in \mathbb{C}^{M\times N}$, vector $\mathbf{x} \in \mathbb{C}^{N\times 1}$ and $\mathbf{b} \in \mathbb{C}^{M\times 1}$ can be explained in details as below:

- Matrix $\mathbf{\Psi} = \{e^{j\phi_{m,n}}\}$ is the designed coefficient matrix with $\phi_{m,n}$ denoting the assigned phase shift value of the n-th subarray for the m-th measurement ($n \in [1, N]$, $m \in [1, M]$).
- Vector $\mathbf{x} = \{x_n\} = \{a_n S_n\}$ with a_n and S_n denoting the initial excitation of the n-th subarray and transmission coefficient between the n-th subarray and the probe antenna, respectively. The diagnosis is achieved by solving the linear equations to obtain the magnitude of x_n. The estimated amplitude of x_n of the failure subarray including i faulty elements should be $\frac{P-i}{P}$ of the normal subarray with $i \in [1, P]$.
- Vector $\mathbf{b} = \{b_m\}$ is the complex array signals measured by the probe antenna with its element b_m denoting the complex signal of the m-th measurement. $\mathbf{b}$ can be directly obtained by measuring S_{21} via a two port vector network analyzer (VNA).

The prerequisite of the proposed method is that the differences in magnitude of S_n is small for all subarrays. Then, the amplitude of $\{x_n\}$ of different subarrays can be considered as the relative amplitude of excitations. The diagnosis can be achieved by comparing the relative excitation amplitude of different subarrays. The approximation requires the probe has low directivity. Moreover, the probe should not be placed too close to the DUT in order to avoid non-negligible imbalance of S_n among different subarrays. To balance the estimation accuracy and the measurement distance, the probe can be placed at the near-field of the whole array but the far-field of the antenna element. Note that this distance might not be enough for array calibration purpose. However, successful array diagnosis results can be expected in this short measurement distance, since it is less demanding in terms of accuracy. Besides, the antenna element used in BS usually has an antenna gain less than 8 dBi indicating element pattern with wide beamwidth. This is also needed for wide angle beam-steering in BS antenna design. Thus, the magnitude difference of S_n caused by the directivity of antenna pattern at the DUT side can be considered as small.

B. Proposed Algorithm

The objective is to obtain the signal amplitude of x_n by solving linear equations in (1). The phase shift value can be set to 0° and 180° in the phase shifter connected to each subarray in the proposed method. The coefficient matrix $\mathbf{A}$ is then designed as:

$$\mathbf{\Psi} = \begin{bmatrix} 1 & 1 & 1 & \ldots & 1 \\ -1 & 1 & 1 & \ldots & 1 \\ 1 & -1 & 1 & \ldots & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & 1 & \ldots & -1 \end{bmatrix} \tag{5}$$

Based on (1) and (5), the $\{x_n\}$ can be solved as

$$x_n = \frac{b_1 - b_{n+1}}{2}. \tag{6}$$

In the first measurement, no phase shift is required for the subarrays. For the following measurements, the phase of the subarray is reversed by introducing 180° phase shift in turns. Thus, the number of the measurements should be $N+1$ to obtain $\{x_n\}$.

As mentioned before, the detection is achieved by comparing the relative signal power of the estimated $\{x_n\}$. In principle, the proposed method can detect n subarray failures ($n \in [1, N]$) with i antenna element failures in one subarray ($i \in [1, P]$). In this paper, we focus on two representative cases i.e. one antenna element failure in a subarray, and one subarray failure (i.e. the whole subarray failure case) since the working principle is the same for other faulty cases. For one antenna element failure detection, the estimated signal power of $\{x_n\}$ of the related subarray should be lower than that of normal subarrays by:

$$D = -20 \lg \frac{P-1}{P}. \tag{7}$$

The value of D decreases as the number of antenna elements, i.e. P increases, e.g. $D = 3.5$ dB when $P = 3$, $D = 1.6$ dB when $P = 6$. The detection accuracy becomes low as P increases due to the noise in the measurements. However, three elements subarrays are the current implementation for 5G base stations. Thus, our discussion is limited to three antenna elements in a subarray. For one subarray failure detection, which is easier than the previous one, the estimated signal power of $\{x_n\}$ of the failure subarray should be 0 in principle.

TABLE I
ANTENNA SPECIFICATION

Antenna type	horn antenna of Vivaldi type
Frequency range (GHz)	2.5-4
HPBW (deg)	54
Dimensions (cm×cm)	30×10

III. MEASUREMENT VALIDATION

A. Measurement system

To experimentally demonstrate the proposed method, an antenna array with 12 antenna elements grouped into 4 subarrays was utilized in the measurement campaigns. The measurement setup diagram and a photo of the measurement system are shown in Fig. 2 and Fig. 3, respectively. The devices used in the measurement campaign are listed as follows:

1) A VNA;
2) 4 digital phase shifters with phase adjustment range of 360° and phase adjustment resolution of 1°;
3) 13 horn antennas of Vivaldi type with 12 of them serving as DUT and the other one as the probe antenna;
4) 5 1-to-4 power splitters and 4 impedance loads.
5) A laptop which controls the phase shifters and communicates with VNA to save the recorded data.

As shown in Fig. 4 (a), a 3 × 4 antenna array was selected from a large antenna array working as DUT in the measurements. It contained four columns of antennas and each column contained three antenna elements grouped as a subarray. The distance between adjacent subarrays is 50 mm (corresponding to half-wavelength at 3 GHz) whereas the element spacing within a subarray is 150 mm (1.5 wavelength). The horn antenna of Vivaldi type shown in Fig. 4 (b) was employed as both the DUT antenna array and the probe antenna. Its specification is listed in Table I. The probe antenna was also selected from a row of antennas located at the boresight direction of the DUT with a distance of 50 cm. Note that the far-field boundary of DUT and antenna element is 320 cm at 3 GHz according to the definition in [13]. The amplitude uncertainty introduced by the digital phase shifter, power splitters and connecting cables is within ±0.4 dB. In the measurement, the signals were generated by VNA, transmitted through power splitters, phase shifters , radiated by DUT and finally received by the probe antenna. The complex array signals caught by the probe antenna were recorded on VNA from 2 to 4 GHz. However, only the signals at 3 GHz were analyzed for simplicity.

B. Measurement Results

Only four typical failures have been investigated in the measurements, i.e. failures of subarray 1, subarray 2, one element in subarray 1, and one element in subarray 2 for simplicity purpose. Subarray 1 was located at the edge of the whole array whereas subarray 2 was in the middle resulting in different electromagnetic environments for these two subarrays. They

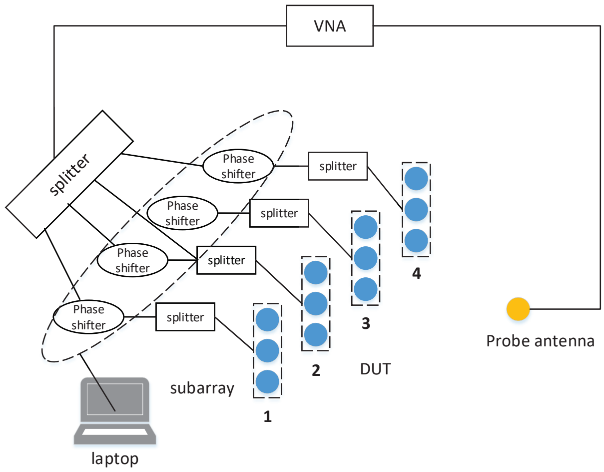


Fig. 2. The diagram of the measurement system.

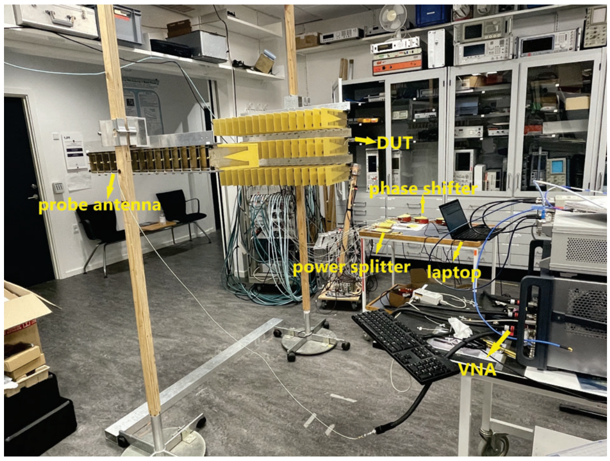
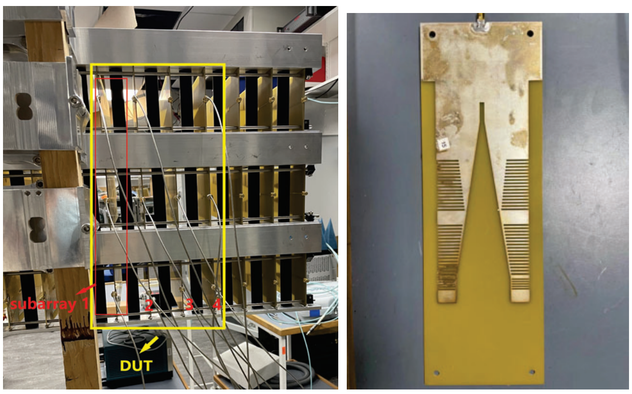


Fig. 3. A photo of the measurement system.



(a) (b)

Fig. 4. The photos of (a) DUT used in the measurement system, and (b) horn antenna of Vivaldi type.

are intentionally selected to validate the robustness of the proposed method. The failures of one subarray and an antenna element were implemented by disconnecting the feed of the subarray at the power splitter side, and the associated antenna feed, respectively. The diagnosis results of the DUT are given in Fig. 5. As discussed before, the estimated amplitude of $\{x_n\}$ is the key point of the diagnosis. In Fig. 5 (a) and (b), the failure subarray can be successfully detected since the normalized estimated signal power of the failure subarray is around 30 dB below the other subarrays. As shown in Fig. 5 (c), the normalized estimated signal power of the subarray 1 and 2 is -3.4 dB and -0.6 dB, respectively whereas the others are around 0 dB. The estimated power of normal subarrays, i.e. subarray 2, 3, and 4 have around 0.6 dB deviation due to the noise and amplitude uncertainty introduced by cables, phase shifters, etc. Nevertheless, the one element failure in subarray 1 can still be detected successfully. Similar results can be observed in Fig. 5 (d).

IV. Conclusion

In this paper, a fast array diagnosis method is proposed for arrays composed of several subarrays in BS. Compared with conventional near-field methods which reconstruct the aperture field based on a large number of samples, the proposed method requires only a few measurements recorded by one single probe. The probe can be placed in the near-field of the DUT antenna array to shorten the measurement distance. The principle of the proposed method is to obtain the estimated excitation amplitude for each subarray and detect the antenna failures within the subarrays. The proposed method was experimentally validated in an antenna array composed of 4 subarrays with each subarray containing 3 elements. The estimated power of a failure subarray was around 30 dB and 3.5 dB below the normal subarrays for the failure of the whole subarray and one antenna element cases, respectively. However, it is hard for proposed method to achieve accurate diagnosis when the subarray contains more than 3 elements. Improvements on the proposed method may be considered in our future work.

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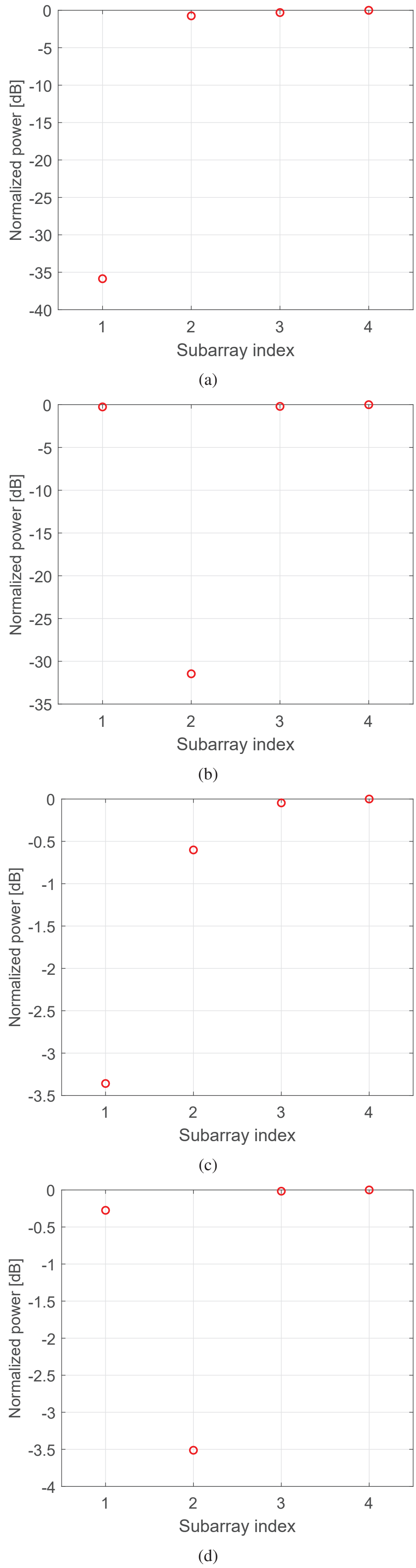

Fig. 5. The normalized estimated signal power for the failures of (a) subarray 1, (b) subarray 2, (c) one antenna element in subarray 1, and (d) one antenna element in subarray 2.

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