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DOA Estimation and Object Localization Based on Multi-harmonic Multi-beam Characteristic of 1-bit Time-Modulated Reflectarray

Xianbo Cao[1a)], Qiang Chen[1], Toru Tanaka[2], Masaki Kozai[2] and Hiroya Minami[2]

[1] *School of Engineering, Tohoku University*
6-6, Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8579, Japan
[2] *Space Environment and Energy Laboratories, NTT*
3-9-11, Midori-cho, Musashino-shi, Tokyo 180-8585, Japan
a) *cao.xianbo.s7@dc.tohoku.ac.jp*

Abstract: A method for direction of arrival (DOA) estimation and object localization based on 1-bit time-modulated reflectarray (TMRA) is presented. The multi-harmonic multi-beam (MHMB) characteristic of 1-bit TMRA is analyzed firstly to reveal the mapping relationship between target's angular feature and received spectrum feature. Then the operating principle and perception procedures for single and multiple targets scenarios are discussed in detail. Benefited from the mapping relationship, the proposed method shows flexibility on simultaneous multi-target detection, which is difficult to realize by conventional methods. Furthermore, the proposed method enables the environment-perception capability of existing 1-bit TMRA without increasing the system complexity, making it suitable for the realization of a low-cost multifunctional reconfigurable intelligent surface (RIS).
Keywords: Time modulation (TM), 1-bit TMRA, DOA estimation, RIS
Classification: Antennas and propagation

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1 Introduction

RIS, defined as an intelligent surface that can flexibly modulate the reflected beam according to the requirements of the application scenario, has been rapidly and extensively studied in recent years as a potential key technology for future communication system such as the sixth-generation (6G) wireless system [1] and autonomous decentralized cooperative power and communication system [2]. With the help of RIS, it is envisioned that a new intelligent architectural paradigm integrating communication, sensing, localization, and recognition will be applied to the aforementioned system.

Among them, TMRA becomes a potential candidate for RIS owing to its powerful beamforming capability which is realized by simultaneous control of units' reflected amplitude and phase [3,4]. Compared to other forms of TMRA, 1-bit TMRA is currently the most investigated because it offers a good compromise between beam control effectiveness, design complexity and cost [5,6]. However, current TMRA research is basically focused on communication applications, while few research has been done to address its applications in aspect of intelligence, such as sensing, localization, and recognition, which should be the significant advantages of RIS.

In this article, we investigated methods to make 1-bit TMRA applied to environmental perception. Specifically, DOA estimation and object localization are realized by utilizing the MHMB characteristic of 1-bit TMRA. More importantly, due to the MHMB characteristic of the TM, the angular domain response of sensed targets can be mapped onto the frequency domain response of the 1-bit TMRA. As a result, the proposed method can clearly and quickly identify multiple targets simultaneously, which is difficult to achieve using conventional methods. Furthermore, the proposed methods only need basic time sequence and common 1-bit TMRA configuration, which makes it easy to realize with low cost.

2 Characteristic Analysis of 1-bit TMRA

2.1 Theory of 1-bit TMRA concept

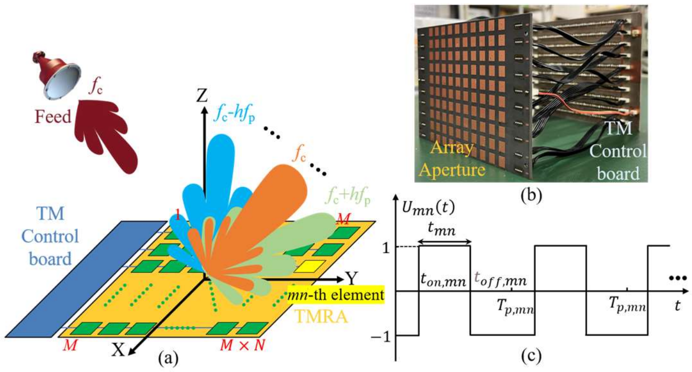

Fig. 1. Typical 1-bit TMRA configuration. (a) System schematic. (b) A 1-bit TMRA prototype in [6]. (c) 1-bit time function.

Fig. 1(a) shows a typical 1-bit TMRA configuration which consists of feed antenna, TMRA and control board. Since the 1-bit TMRA is designed for RIS application, the feed antenna's location is placed in its far-filed. The TMRA has the same structure with 1-bit RA whose elements have two states with opposite phase. The pre-designed specific time function generated by the control board is used to high-speed switch the states of reflection of each element, and thus realize the control of reflected beam. Fig. 1(b) shows a photo of a 1-bit TMRA prototype from our previous work [6]. Fig. 1(c) shows the 1-bit time function $U_{mn}(t)$ which has two level stages. For the mn-th element, the switch is switched to the two states periodically, and the corresponding turning times are denoted as $t_{on,mn}$ and $t_{off,mn}$, where $kT_{p,mn} \leq \tau_{on,mn} \leq \tau_{off,mn} \leq (k+1)T_{p,mn}$ and $T_{p,mn}$ is the time of a complete switching cycle (denoted as a TM period), and k is an integer. Under these conditions, the scattering waveform generated by the TMRA with the term $e^{j2\pi f_0 t}$ explicitly included is mathematically expressed as

$$f(t,\theta,\varphi) = e^{j2\pi f_0 t} F_0(\theta,\varphi) U_{mn}(t) \tag{1}$$

where f_0 is the frequency of the illuminating continues wave (CW) signal, $F_0(\theta,\varphi)$ is the static scattering pattern of the array at center frequency f_0. Controlled by the 1-bit time function, the corresponding Fourier series coefficients $a_{h,mn}$ of the mn-th element can be expressed as

$$a_{h,mn} = \frac{1}{T_{p,mn}} \int_{t_{on,mn}}^{t_{off,mn}} g_{mn}(t) e^{-j2\pi h f_{p,mn} t} dt = \begin{cases} 2\dfrac{\sin(\pi h \tau_{mn})}{\pi h} e^{-j\pi h(\tau_{off,mn}+\tau_{on,mn})}, & h \neq 0 \\ 2\tau_{mn}, & h = 0 \end{cases} \tag{4}$$

where $g_{mn}(t)$ is one period of $U_{mn}(t)$. The $\tau_{on,mn}$ and $\tau_{off,mn}$ are the normalized turn on/off times of the mn-th element and are defined by $\tau_{on,mn} = t_{on,mn}/T_{p,mn}$ and $\tau_{off,mn} = t_{off,mn}/T_{p,mn}$. The τ_{mn} is the switch-on duration and is defined by $\tau_{mn} = \tau_{off,mn} - \tau_{on,mn}$. TM frequency $f_{p,mn}$ is defined as the inverse of the TM period $T_{p,mn}$.

Therefore, the scattering pattern of the h-th harmonic frequency component of 1-bit TMRA can be expressed as:

$$f_h(t,\theta,\varphi) = e^{j2\pi(f_0 + h f_{p,mn})t} F_0(\theta,\varphi) a_{h,mn} \tag{5}$$

It can be found that $a_{h,mn}$, acting as an additional excitation, is added to each element, by which the scattering pattern of the array can be controlled. As a result, the 1-bit TMRA introduces a new degree of freedom to meet more challenging requirements of RIS applications.

2.2 Multi-harmonic multi-beam (MHMB) characteristic

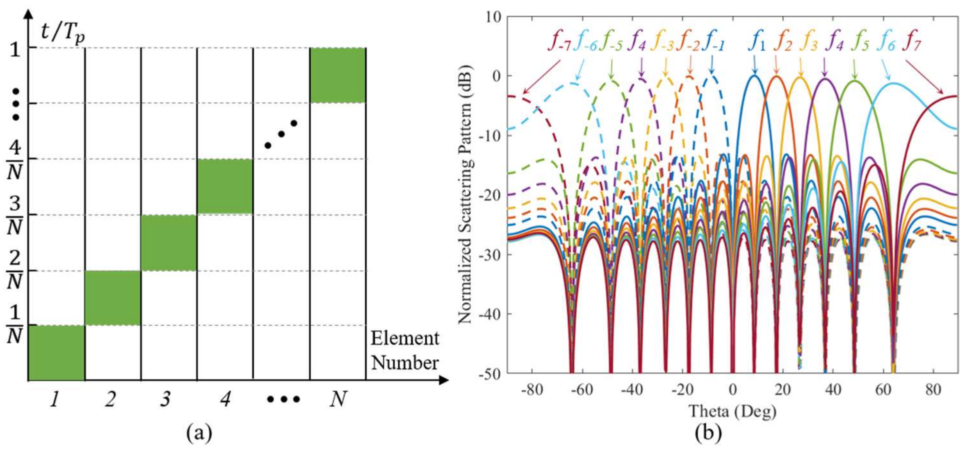

Fig. 2. MHMB characteristic of 1-bit TMRA. (a) Scanning time sequence. (b) Corresponding scattering patterns.

As $a_{h,mn}$ is the equivalent excitation introduced by TM, different time functions correspond to other $a_{h,mn}$ and thus leads to different control effect of 1-bit TMRA. Here we consider a N-element linear 1-bit TMRA to illustrate the MHMB characteristic of 1-bit TMRA. As shown in Fig. 2(a), a specific set of time function, called scanning time sequence, is applied to the array. Specifically, array's elements are "lit up" (i.e., one state of 1-bit function) in sequence and remain "off" (i.e., the other state of 1-bit function) at other times, as expressed in Eq. (6). In Fig. 2(a), the green zone corresponds to "1" state and others correspond to "-1" state. Note that the TM period T_p is same for each element.

$$g_n(t) = \begin{cases} 1, & \frac{n-1}{N}T_p \le t \le \frac{n}{N}T_p, \ 1 \le n \le N \\ -1, & elsewhere \end{cases} \tag{6}$$

It can be referred from Eq. (2) and Eq. (6) that by the utilizing scanning time sequence the equivalent excitations of different harmonics would have same amplitudes and progressive phases. This would generate a specific set of scattering patterns. Fig. 2(b) shows the theoretical calculation results of harmonics' scattering patterns for a linear 1-bit TMRA with 20 elements. A plane wave with vertical incidence is used to illuminate 1-bit TMRA in calculation. It can be observed that the main beams of different harmonics appear sequentially and point to adjacent directions as the harmonic order changes, achieving multi-beam coverage in a large angular range. Note that the direction of the reflected wave at the center frequency is the specular reflection direction of the incident wave. This unique combination of harmonic scattering patterns is named MHMB characteristic, which is only determined by time sequence and element number. That is, the deviation angles of each harmonic beam direction relative to the center frequency's beam direction are known. As a result, the beam direction of a certain harmonic can be easily derived if its order and the beam direction of center frequency is known, which is the principle for applying 1-bit TMRA to realize DOA estimation and object localization.

3 Principle of applying 1-bit TMRA for DOA estimation and object localization

3.1 Single target scenario

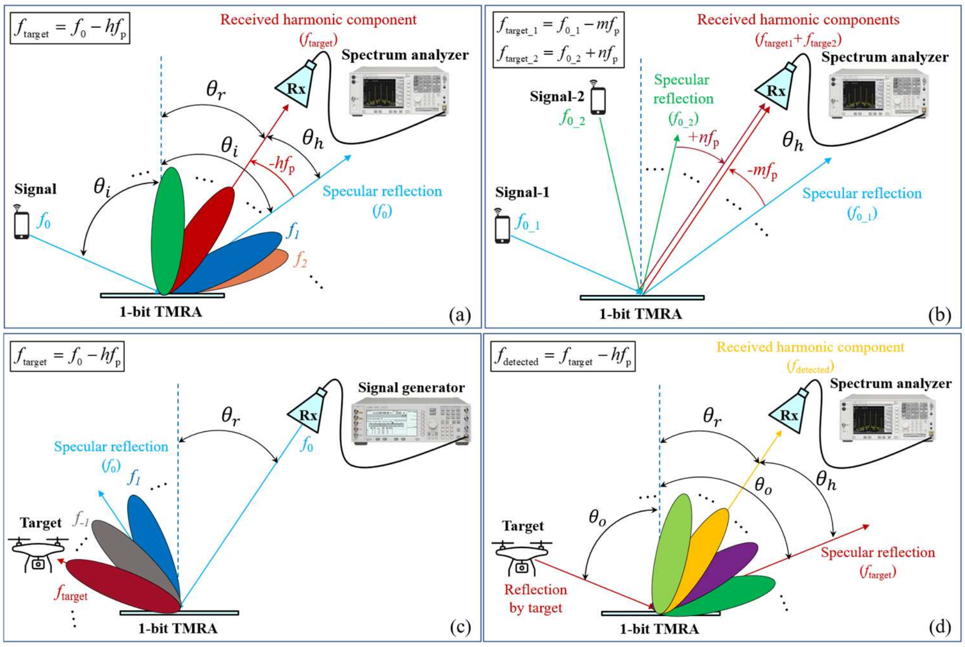

Fig. 3. Principles and methods of environmental perception. (a) Single target DOA estimation. (b) Multi-target DOA estimation. (c) Single target object localization: first step. (d) Single target object localization: second step.

Fig. 3(a) shows the schematic diagram of 1-bit TMRA applied to DOA estimation. Both the receiving antenna (Rx) and the incoming signal to be recognized are located in the far-field region of the 1-bit TMRA. The angles of the Rx and the incoming signal with respect to the normal of the aperture of 1-bit TMRA are θ_r and θ_i, respectively. When the incoming signal with an operating frequency of f_0 propagates to the 1-bit TMRA controlled by the scanning time function with a TM frequency of f_p, it would be reflected towards different directions with different frequencies based on HMHB characteristic. Now we have $\theta_i = \theta_r + \theta_h$, where θ_h is the angle between the direction of the received harmonics and the Rx direction. Based on the aforementioned mapping relationship, the DOA can be derived from the spectrum response of signal captured by Rx. Once the dominant harmonic component (has maximum power level), denoted as f_{target}, is found from the spectrum response, the order of dominant harmonic can be obtained as $h_{\text{target}} = \frac{f_{\text{target}} - f_0}{f_p}$. Then θ_h can be obtained from the Fig. 2(b) by comparing the beam direction difference with $f_{h_{\text{target}}}$ and center f_0. As a results, θ_i is derived, indicating a completed DOA estimation of incoming signal.

Furthermore, object localization can also be realized based on the MHMB characteristic of 1-bit TMRA. In this application, the antenna first sends a CW signal with frequency of f_0 to the 1-bit TMRA, and a specific harmonic component (denoted as f_{target}) of the scattering waves would impinge the target, as shown in Fig. 3(c). Then the target would reflect the wave of f_{target} component towards 1-bit TMRA. Accordingly, f_{target} component would be scattered again under the effect of TM, as shown in Fig. 3(d). The following procedures are as same as the analysis of DOA estimation. Note that if the final detected dominant harmonic component is f_{detected}, the actual order of harmonic which carries target's angular feature $h_{\text{target}} = \frac{1}{2} \cdot h_{\text{detected}} = \frac{1}{2} \cdot \frac{f_{\text{detected}} - f_0}{f_p}$. Thus, θ_h is obtained and the direction of object can be derived by $\theta_o = \theta_r + \theta_h$.

3.2 Multi-target scenario

Since different directions correspond to different harmonic components, it is possible to simultaneously realize multi-target perception. Limited by the paper length, here we only give an example of multi-target DOA estimation scenario to concisely demonstrate the operating principle. As shown in Fig. 3 (b), there are two user signals with different operating frequencies of f_{0_1} and f_{0_2}. Different from the single target scenario, two dominant harmonic components would appear in the spectrum response results and correspond to two detected directions. The other procedure of perception is as same as single target scenario. Note that the operating frequencies of targets should be different to each other to ensure the TM effect. Moreover, to avoid overlap of targets' signal, the operating frequencies of each target f_{0_m} should satisfy the following equation $f_{0\_i} - f_{0\_j} \neq nf_p, i, j \in m, i \neq j, n \in Z$.

4 Conclusion

A method to utilize the MHMB characteristic of 1-bit TMRA for DOA estimation and object localization was presented in this article. The theoretical calculation results show that the MHMB characteristic establishes a mapping relationship between angular domain and frequency domain, which is suitable for realizing environmental perception. On this basis, the perception principle and procedures of DOA estimation and object localization for both single target and multi-target scenarios were illustrated and discussed in detail. Practical consideration regarding to avoid overlap of targets' signal is also discussed. The effectiveness of the proposed method needs to be verified by further experimental studies. Nevertheless, the findings of this study can be used as a resource for refining the theory of environmental perception technology and extending the applications of 1-bit TMRA.

Acknowledgments

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