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One-bit quantization is good for programmable coding metasurfaces

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Abstract The information-carrying programmable metasurfaces have found widespread applications in communication, sensing, and other related areas. However, there is a fundamental but unresolved problem, i.e., the rigorous understanding of the quantization of metasurface coding. Here, we theoretically investigate the performance difference between one-bit and continuous information-encoding metasurfaces. To this end, we derive analytical representations of system responses in various cases (single-input single-output, single-input multiple-output, and multiple-input multiple-output). We analyze the impact of one-bit coding (in contrast to continuous coding) in terms of the resulting channel cross-talk and reduction of information capacity in various representative scenarios from wireless communication and holography. Our main finding indicates that the one-bit coding yields a satisfactory performance in most practical scenarios; we also show that in many cases there are smart ways to mildly relax optimization constraints in order to reduce the performance gap between the one-bit and continuous coding. We expect that our results can provide theoretical guidance for a large variety of metasurface-assisted information systems for electromagnetic waves and other wave phenomena.

Keywords metasurfaces, metamaterials, information capacity, signal representation, one-bit coding metasurface

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1 Introduction

The ability to manipulate information-carrying electromagnetic (EM) fields pivotally underpins wireless communication, imaging and sensing, wireless power transfer, and other related areas. It has received long-standing interests in fundamental sciences, engineering, and military contexts. Modern information systems typically rely on massive antenna arrays in combining with beamforming techniques to simultaneously improve the range of wireless links and reduce unwanted interference [1–4]. However, the bulky, costly, and power-hungry hardware increasingly struggles to meet the requirements of ever-increasing amounts of connection nodes, especially with the advent of "green" Internet of Things (IoT). An emerging alternative paradigm for EM wave manipulation is using programmable coding metasurfaces [5, 6], which are composed of ultrathin and inexpensive arrays of in-situ reprogrammable meta-atoms. The programmable coding metasurface has become an emerging member of a large family of metasurfaces holding large technological promise owing to their ability to manipulate the EM waves in a flexible manner. Initially, the programmable metasurfaces were designed to serve on the transmit side in combination with a carefully deployed source antenna [5, 7–12], as an alternative to the low-cost phased array antennas

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for beam forming in free space. Generally, they can be understood as a multi-port device linking various input channels (sources) to various output channels (receivers) in an adaptive manner in terms of geometrical (number and location) and physical (signal response) port properties. Moreover, the programmable metasurfaces can be integrated into the propagation environment itself [13], as an alternative relaying mechanism in (quasi) free space [14–17] to optimize the available channels in scattering environments [18] or to conceive unconventional backscatter communication protocols [19, 20].

To date, many practical realizations of the programmable metasurfaces rely on one-bit (or few bit) coding in order to further reduce the system cost, complexity, and energy consumption. A one-bit meta-atom is controlled with an externally applied one-bit voltage, and correspondingly has two distinct response states denoted by '0' and '1'. For instance, upon illumination with a plane wave, the state '0' ('1') may correspond to a reflection phase of 0° (180°). Given the success of one-bit coding in diverse applications including wireless communications, imaging and sensing [21–29], wireless power transfer [30, 31], programmable holography [32], and analog computing [33], a fundamental question [34, 35] arises: what is the achievable information capacity of a programmable metasurface built with one-bit coding meta-atoms (reflection coefficient $R = \pm 1$) compared with the ideal case of continuously tunable meta-atoms ($R = A\exp(\mathrm{j}\varphi)$ with the amplitude $|A| \leqslant 1$ and $0 \leqslant \varphi < 2\pi$)? Interestingly, related questions about the impact of quantization on focusing (but not on programmable information encoding) have already arisen in related but distinct areas of wave engineering such as diffractive optical and acoustic elements (e.g., Fresnel lenses) [36–38], time reversal [39], and optical wavefront shaping in the complex media [40]. Very recently, the impact of the programmable metasurface quantization has received attention from a signal-processing perspective for the simplest case of single-input single-output (SISO) scenarios, in which the metasurface serves as an alternative relaying mechanism without encoding any information [41–44].

To comprehensively explore the quantization effects for information-encoding programmable metasurfaces operating in (quasi) free space, here we first derive the mathematical representations of the one-bit coding system response for three representative scenarios: SISO, single-input multiple-output (SIMO), and multiple-input multiple-output (MIMO). These scenarios link one or multiple input channels to one or multiple output channels. Our analysis reveals that the one-bit quantization gives rise to undesirable effects like energy leakage, parasitic unwanted beams, and channel cross-talk. We also find that in many practical applications the performance deterioration is negligible and can be limited under mild constraint relaxations. Then, we derive analytical expressions for the signal interferences and the reduction in channel capacity. Moreover, we illustrate our theoretical findings with concrete examples of programmable holography and wireless communications. We expect that our results can provide valuable guidance for the designs of the current and future metasurface-assisted EM information systems in wireless communications and sensing, as well as for various applications at other frequencies [45–52].

2 Representation of system response in one-bit coding metasurface

To start, we derive the system response of one-bit programmable coding metasurface acting as a reprogrammable wireless multi-port device that links various incident beams (from sources) to various outgoing beams (to receivers). To avoid complications due to the EM coupling effects, we group several adjacent meta-atoms together to form a "macro meta-atom". We then assume that the metasurface shown in Figure 1 is composed of $M \times N$ macro meta-atoms that can be modeled as having mutually independent EM responses. For convenience, we refer to the "macro meta-atom" as meta-atom hereafter.

2.1 Case I: SISO

For SISO, the one-bit coding metasurface is used to establish a wireless channel linking a source at $\boldsymbol{r}_s$ with an intended receiver at $\boldsymbol{r}_q$, as shown in Figure 1(a). This wireless link is easily established by suitably programming the metasurface. We assume that the signal power level of the source is $\mathcal{P}$; and the signal is desired to acquire a phase ϕ_q $(0 \leqslant \phi_q < 2\pi)$ when it reaches $\boldsymbol{r}_q$ in a phase shift keying (PSK) scheme. We emphasize that, throughout this work, the information is not encoded by the source at $\boldsymbol{r}_s$ but through the modulation of EM wave by the metasurface. However, the scenario of information being encoded by the source is a special case of our model, where only the intensity of the radiation beam is concerned. A closed-form estimate of a suitable one-bit coding pattern of the metasurface for this purpose is $\mathcal{C}^{\mathrm{SISO}}_{m,n} = \mathrm{sign}[\cos(\tilde{\phi}^{\mathrm{SISO}}_{nm})]$, where $\tilde{\phi}^{\mathrm{SISO}}_{nm} \equiv \tilde{\phi}_{m,n}(\boldsymbol{r}_q; \boldsymbol{r}_s)$ and $\tilde{\phi}_{m,n}(\boldsymbol{r}_q; \boldsymbol{r}_s) =$

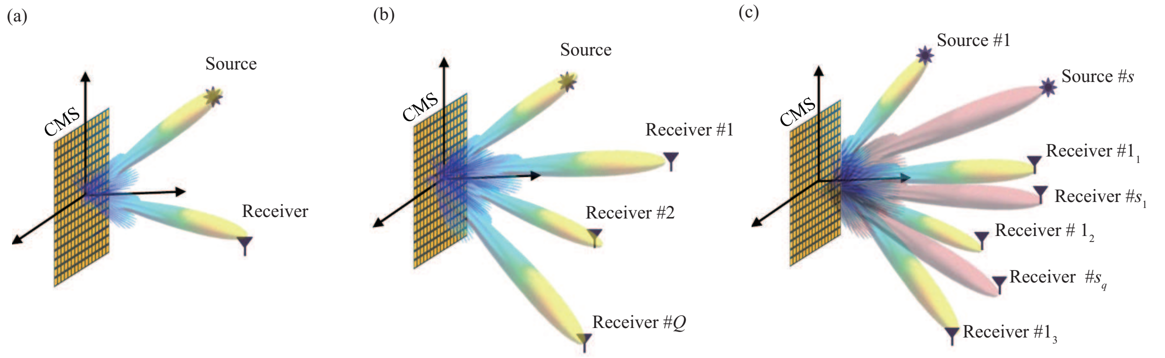

Figure 1 (Color online) Illustration of how a programmable coding-metasurface (CMS) acts as a wireless multiple-port device. (a) SISO: CMS serves as a wireless ultrathin device with one input port and one output port, linking one source to one intended receiver. (b) SIMO: CMS serves as a single-input multiple-output wireless device, connecting one source with Q ($Q>1$) intended receivers (Receiver #1, Receiver #2, ..., Receiver #Q). (c) MIMO: CMS serves as a wireless ultrathin device with S input ports and $\sum_{i=1}^{S} Q_i$ output ports. Each source (e.g., Source #s, $s=1,2,\ldots,S$) is linked to Q_i intended receivers (i.e., Receiver #s s_1, Receiver #s, ..., Receiver #s_{Q_s}) by CMS.

$\Delta_{m,n}(\boldsymbol{r}_q;\boldsymbol{r}_s)+\phi(\boldsymbol{r}_q)$, $\Delta_{m,n}(\boldsymbol{r}_q;\boldsymbol{r}_s)=k(\underbrace{|\boldsymbol{r}_s-\boldsymbol{r}_{m,n}|}_{R_{nm}(\boldsymbol{r}_s)}+\underbrace{|\boldsymbol{r}_q-\boldsymbol{r}_{m,n}|}_{R_{nm}(\boldsymbol{r}_q)})$. Herein, k denotes the wavenumber in free-space, and $\boldsymbol{r}_{m,n}$ denotes the location of metasurface element. Considering that the real location of the source $\boldsymbol{r}'$ is usually inaccurate or even unknown [19], we assume that the estimated location of the source is $\boldsymbol{r}_s$. Then, the response at $\boldsymbol{r}$ can be derived as (see details in Appendix A)

$$\widehat{\mathcal{H}}_{\mathrm{SISO}}(\boldsymbol{r},\boldsymbol{r}';q,s)=\underbrace{E_1^{\mathrm{SISO}}(\boldsymbol{r},\boldsymbol{r}';q,s)}_{\text{leading term}}+\underbrace{\sum_{p=-\infty,p\neq 1}^{\infty} B_p^{\mathrm{SISO}}A_p^{\mathrm{SISO}}(\boldsymbol{r},\boldsymbol{r}';q,s)\exp(\mathrm{j}p\phi_q)}_{\text{perturbation terms}},\tag{1}$$

where j is the imaginary unit,

$$E_1^{\mathrm{SISO}}(\boldsymbol{r},\boldsymbol{r}';q,s)=B_1^{\mathrm{SISO}}A_1^{\mathrm{SISO}}(\boldsymbol{r},\boldsymbol{r}';q,s)\exp(\mathrm{j}\phi_q),$$
$$A_p^{\mathrm{SISO}}(\boldsymbol{r},\boldsymbol{r}';q,s)=\sum_{m,n}\frac{\exp[\mathrm{j}(p\Delta_{nm}(\boldsymbol{r}_q;\boldsymbol{r_s})-\Delta_{nm}(\boldsymbol{r};\boldsymbol{r}'))]}{R_{nm}(\boldsymbol{r})R_{nm}(\boldsymbol{r}')},$$
$$B_p^{\mathrm{SISO}}=\begin{cases}-\frac{\mathrm{j}^{p+1}}{\pi}\frac{2}{p}, & \text{if } p \text{ is odd},\\ 0, & \text{else.}\end{cases}$$

Note that $|B_1^{\mathrm{SISO}}|=|B_{-1}^{\mathrm{SISO}}|$ and $R_{nm}(\boldsymbol{r})=|\boldsymbol{r}-\boldsymbol{r}_{m,n}|$, where $\boldsymbol{r}_{m,n}$ denotes the location of the (m,n) meta-atom. Eq. (1) offers several important insights. First, we note that the leading term E_1^{SISO} represents the system response of continuous metasurface but corrected by a multiplicative factor of $B_1^{\mathrm{SISO}}=\frac{2}{\pi}\sim 0.64$ (corresponding to about 3 dB energy loss). Meanwhile, the perturbation terms characterize the unwanted parasitic beams that divert the energy from the source into directions other than that of the intended receiver due to the one-bit quantization of the meta-atom programmability.

To illustrate the roles of different terms, we plot spatial maps of $|\widehat{\mathcal{H}}_{\mathrm{SISO}}|$ for representative cases. Firstly, we consider two cases for which the source and intended receiver are in the near field of the metasurface. For a receiver on or off the 0° azimuth, Figures 2(a) and (b) respectively show plots of $|\widehat{\mathcal{H}}_{\mathrm{SISO}}|$ both with continuous and one-bit coding metasurfaces. Additionally, the first a few nonzero terms $|E_p^{\mathrm{SISO}}|$ are visualized. In both cases, we observe that the leading term $p=1$ dominates the system response $|\widehat{\mathcal{H}}_{\mathrm{SISO}}|$ and there is no significant difference between the continuous coding and one-bit coding. While the focus is about 3 dB weaker with the one-bit coding, and the quantization energy loss is statistically uniformly distributed over the entire space. Overall, in these two cases the performance of one-bit coding is of comparable quality to that with the continuous coding.

Next, we consider two similar scenarios in Figures 2(c) and (d) for which both source and intended receiver are in the far field region. Here, the perturbation terms ($p\neq 1$) have non-negligible contributions to the system responses $|\widehat{\mathcal{H}}_{\mathrm{SISO}}|$ but can be truncated at the number of calculated terms $P=3$ (root

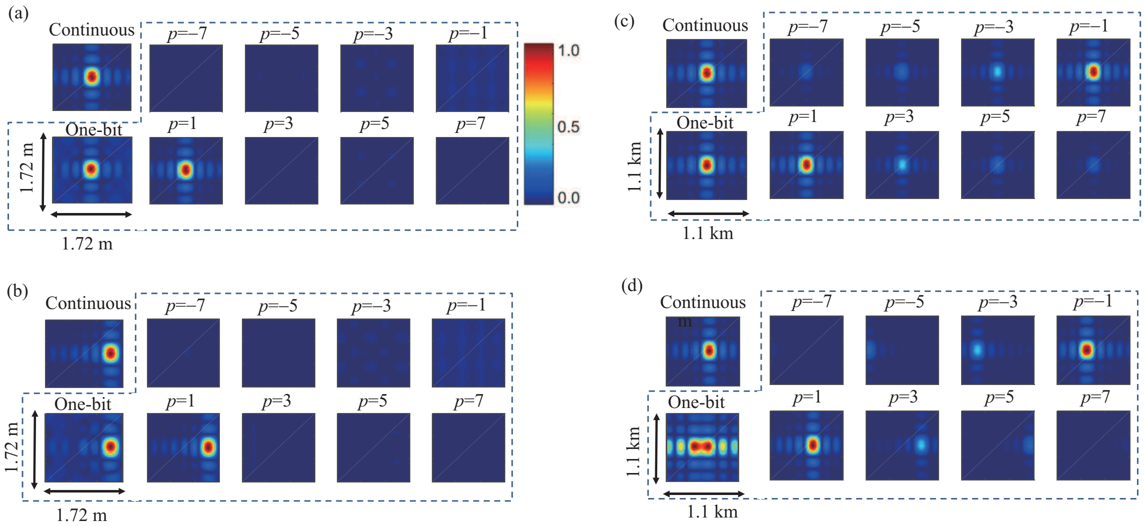

Figure 2 (Color online) Spatial maps of $|\widehat{\mathcal{H}}_{\rm SISO}|$ for continuous and one-bit coding metasurfaces, as well as the maps of $|E_p^{\rm SISO}|$ for $p=\pm1,\pm3,\pm5,\pm7$ in the one-bit coding case, in which the maps titled with continuous are normalized their own maximums, and the other maps are normalized by $|E_1^{\rm SISO}|$. Different source and receiver locations are considered: (a) $\boldsymbol{r}_s=(0,0,1.2)$ m, $\boldsymbol{r}_q=(0,0,3)$ m; (b) $\boldsymbol{r}_s=(0,0,1.2)$ m, $\boldsymbol{r}_q=(0,0.6,3)$ m; (c) $\boldsymbol{r}_s=(0,0,1)$ km, $\boldsymbol{r}_q=(0,0,2)$ km; (d) $\boldsymbol{r}_s=(0,0,1.2)$ km, $\boldsymbol{r}_q=(0,0.1,2)$ km.

mean square error (RMSE) $< 0.5\%$). Unless the receiver is at the 0° azimuth, multiple unwanted parasitic beams interfere with the desired beam. In particular, the $p=-1$ term appears to be mirror-symmetrical with respect to the normal direction $\widehat{\boldsymbol{n}}$ of the one-bit coding metasurface. More details can be found in Appendix B.

To shed more light on these far-field limitations, we simplify the $E_p^{\rm SISO}$ terms under a farfield approximation:

$$E_p^{\rm SISO}(\boldsymbol{r},\boldsymbol{r}_s;q,s)\approx B_p^{\rm SISO}MN\frac{\exp\left[{\rm j}k\left(pr_q-r+(p-1)r_s\right)\right]}{rr_s}\exp\left({\rm j}p\phi_q\right),\ \text{for}\ \hat{\boldsymbol{r}}-p\hat{\boldsymbol{r}}_q+(1-p)\hat{\boldsymbol{r}}_s\|\widehat{\boldsymbol{n}},\quad(2)$$

where let the symbol $\boldsymbol{a}\|\boldsymbol{b}$ denote that the vector $\boldsymbol{a}$ is parallel to the vector $\boldsymbol{b}$.

Then the desired beam ($p=1$) in the far-field approximation is

$$E_1^{\rm SISO}(\boldsymbol{r},\boldsymbol{r}_s;q,s)\approx B_1^{\rm SISO}MN\frac{\exp\left[{\rm j}k\left(r_q-r\right)\right]}{rr_s}\exp\left({\rm j}\phi_q\right),\quad \text{for}\ \hat{\boldsymbol{r}}=\hat{\boldsymbol{r}}_q,\quad(3)$$

and there are multiple significant unwanted parasitic beams corresponding to the values of $p\neq1$. In particular, the expression for the $p=-1$ term in the far-field region is written as

$$E_{-1}^{\rm SISO}(\boldsymbol{r},\boldsymbol{r}_s;q,s)\approx B_{-1}^{\rm SISO}MN\frac{\exp\left[-{\rm j}k\left(r_q+r-2r_s\right)\right]}{rr_s}\exp\left(-{\rm j}\phi_q\right),\ \text{for}\ \hat{\boldsymbol{r}}_q+\hat{\boldsymbol{r}}+2\hat{\boldsymbol{r}}_s\|\widehat{\boldsymbol{n}},\quad(4)$$

where $|B_1^{\rm SISO}|=|B_{-1}^{\rm SISO}|$ confirms the previous observation in Figure 2(d) of mirror-symmetry to the desired beam in terms of amplitude; and now it is 180° out of phase with the desired beam.

For the special case with $\hat{\boldsymbol{r}}_q=\hat{\boldsymbol{r}}_s=\widehat{\boldsymbol{n}}$ from Figure 2(c), the focusing ability of the one-bit coding programmable metasurface is acceptable because all undesired beams (especially $p=-1$) point to the 0° azimuth direction. This assumption holds in this realistic scenario that the metasurface is normally illuminated by a plane wave, and the receiver is mounted at the 0° azimuth. However, focusing is only the prerequisite and not sufficient condition for our goal to use the programmable metasurface as information encoding. For concreteness, we consider phase shift keying (PSK).

When $\hat{\boldsymbol{r}}_q=\hat{\boldsymbol{r}}_s=\widehat{\boldsymbol{n}}$, we have

$$E_p^{\rm SISO}(\boldsymbol{r},\boldsymbol{r}_s;q,s)=B_p^{\rm SISO}MN\frac{1}{rr_s}\exp\left({\rm j}p\phi_q\right).\quad(5)$$

Thus the SISO system response reads

$$\widehat{\mathcal{H}}_{\rm SISO}(\boldsymbol{r}_q,\boldsymbol{r}_s;q,s)=\frac{2MN}{rr_s}\sum_{p=1}^{\infty}B_p^{\rm SISO}\cos\left(p\phi_q\right).\quad(6)$$

We observe that $\widehat{\mathcal{H}}_{\rm SISO}\left(\boldsymbol{r}_q,\boldsymbol{r}_s;q,s\right)$ is a real number in this case, preventing the metasurface from achieving high-level PSK beyond binary phase shift keying (BPSK).

2.2 Case II: SIMO and MIMO

We first consider the SIMO setting, in which a single source at $\boldsymbol{r}_s$ is linked to Q ($Q>1$) receivers via directive radiation beams, upon interacting with the metasurface. The qth beam is aimed at the intended receiver at $\boldsymbol{r}_q$ with desired phase ϕ_q ($0\leqslant\phi_q<2\pi$) for the PSK information encoding. For this purpose, the closed-loop estimate of the required one-bit control coding pattern of the metasurface is $\mathcal{C}_{m,n}^{\rm SIMO}={\rm sign}[\sum_{q=1}^{Q}\cos(\tilde{\phi}_{nm}^{\rm SIMO}(q))]$, where $\tilde{\phi}_{nm}^{\rm SIMO}(q)\equiv\tilde{\phi}_{m,n}\left(\boldsymbol{r}_q;\boldsymbol{r}'\right)$. Following similar steps as before, we obtain the system response of the one-bit coding metasurface at $\boldsymbol{r}$ as

$$\begin{aligned}\widehat{\mathcal{H}}_{\rm SIMO}\left(\boldsymbol{r},\boldsymbol{r}';\{q\},s\right)=&\underbrace{E_1^{\rm SIMO}\left(\boldsymbol{r},\boldsymbol{r}';\{q\},s\right)}_{\text{leading term}}\\&+\underbrace{\sum_{\{p_q\}/\left\{\sum_q|p_q|=1\&p_q\neq-1\right\}}E_{\{p_q\}}^{\rm SIMO}\left(\boldsymbol{r},\boldsymbol{r}';\{q\},s\right)\exp\left[{\rm j}\sum_{q=1}^{Q}p_q\phi_q\right]}_{\text{perturbation terms}},\end{aligned}\tag{7}$$

where $\{q\}$ denotes a collection of Q receivers at different locations, and $\{p_q\}$ is a collection of Q harmonic orders which comes from the aforementioned Q receivers one by one. In (7),

$$\begin{aligned}E_1^{\rm SIMO}\left(\boldsymbol{r},\boldsymbol{r}';\{q\},s\right)&=B_1^{\rm SIMO}\sum_{q=1}^{Q}\exp\left({\rm j}\phi_q\right)A_1^{\rm SISO}\left(\boldsymbol{r},\boldsymbol{r}';q,s\right),\\E_{\{p_q\}}^{\rm SIMO}\left(\boldsymbol{r},\boldsymbol{r}';\{q\},s\right)&=B_{\{p_q\}}^{\rm SIMO}A_{\{p_q\}}^{\rm SIMO}\left(\boldsymbol{r},\boldsymbol{r}';\{q\},s\right),\end{aligned}$$

where $B_{\{p_q\}}^{\rm SIMO}=-\frac{\rm j}{\pi}{\rm j}^{\sum_{q=1}^{Q}p_q}\int_{-\infty}^{\infty}\frac{1}{\xi}\prod_{q=1}^{Q}J_{p_q}(\xi){\rm d}\xi$, $B_1^{\rm SIMO}=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{1}{\xi}J_1(\xi)J_0^{Q-1}(\xi){\rm d}\xi$ and $A_{\{p_q\}}^{\rm SIMO}(\boldsymbol{r},\boldsymbol{r}';\{q\},s)=\sum_{m,n}\frac{\exp({\rm j}[\sum_{q=1}^{Q}p_q\Delta_{m,n}(\boldsymbol{r}_q;\boldsymbol{r}_s)-\Delta_{m,n}(r;\boldsymbol{r}')])}{R_{nm}(\boldsymbol{r})R_{nm}(\boldsymbol{r}')}$. Note that $B_{\{p_q\}}^{\rm SIMO}=0$ when $\sum_{q=1}^{Q}|p_q|$ is an even number. More details about (7) are presented in Appendix C. As before, the Q-fold multiple summation of the second term in (7) can be approximated with an accuracy of RMSE $<0.5\%$ under the condition of $\sum_q|p_q|\leqslant3$.

Similar to the case of SISO, the leading term $E_1^{\rm SIMO}$ in (7) describes the system response of the corresponding continuous metasurface but with a multiplicative factor of $B_1^{\rm SIMO}$. The collection $\{p_q\}/\{\sum_q|p_q|=1\ \&\ p_q\neq-1\}$ describes the energy leakages due to the one-bit quantization in comparison to the continuous coding metasurface. Moreover, signal interferences and cross talks between different intended receivers arise due to the one-bit coding, which will be studied in the subsequent section. For completeness, a generalization of the presented SIMO results to the MIMO situation has been included in Appendix D.

Before closing this section, we provide more insights into the relation of the system response between the one-bit and continuous coding metasurface. To that end, we accurately construct the system response of the continuous metasurface by linearly weighting K system responses of the one-bit coding metasurface. Note that these K system responses correspond to K different coding patterns of the one-bit coding metasurface. The K coding patterns of the one-bit metasurface can be designed such that the one-bit coding metasurface will produce the same radiation patterns but with K distinct radiation phases (i.e., K-level PSK) at the locations of the intended receivers. We illustrate it in the following for the SISO case. Assuming that the desirable system response of a continuous coding metasurface has the phase ϕ ($0\leqslant\phi<2\pi$) at an intended receiver at $\boldsymbol{r}$, then the desirable system response of the continuous coding metasurface can be constructed. With reference to (1), the one-bit coding metasurface with the kth coding pattern will produce the system response $\widehat{\mathcal{H}}_{\rm SISO}^{(k)}(\boldsymbol{r};q,s)$ with the intended phase $\phi_q^{(k)}$ at the receiver at $\boldsymbol{r}_q$ ($k=1,2,\ldots,K$). Then, substituting (1) into the first term $A_1^{\rm SISO}\left(\boldsymbol{r},\boldsymbol{r}';q,s\right)$ in (A3) leads to the following $2P$ linear equations:

$$\begin{cases}\sum_{k=1}^{K}w_k\exp\left({\rm j}\phi_q^{(k)}\right)=\frac{\pi}{2}\exp({\rm j}\phi)+\epsilon,\\\sum_{k=1}^{K}w_k\exp\left({\rm j}p\phi_q^{(k)}\right)=\epsilon,\quad p=-1,\pm2,\ldots,\pm P,\end{cases}\tag{8}$$

where ϵ denotes the approximation error. To determine the K weighting factors $\{w_k\}$, a classical minimum mean-least-square method can be applied to (8). We find that when the receiver and/or sources are not in the "blind district" of the one-bit coding metasurface (i.e., the perturbation terms are negligible compared with the leading term), we can use the one-bit coding metasurface with 2 different control coding patterns to approximate the system response of the ideal metasurface. A thorough study of the minimum required value of K in the SIMO case is provided in Discussion 5 of Appendix C. Interestingly, we observe a clear link between the required minimum value of K to approximate the ideal metasurface response reasonably well and the ratio $Q/\gamma_{\text{one-bit}}$, where $\gamma_{\text{one-bit}}$ is the multiplicative factor $\left(B_1^{\text{SISO}}, B_1^{\text{SIMO}} \text{ or } B_1^{\text{MIMO}}\right)$ between the desired $p=1$ one-bit coding system response term and the continuous coding system response (see details in Appendix C).

3 Signal interferences due to one-bit coding

The one-bit quantization of the coding metasurface gives rise to the quantization-related signal interferences between different channels in SIMO and MIMO settings. In the context of wireless communication, this yields so-called channel cross talk; while in the context of sensing, this results in image blurring. We now study this effect for concreteness in SIMO, but the developed results can easily be extended to MIMO. Throughout this section, we assume that the source and receivers are not in the "blind district", i.e., the perturbation terms are negligible compared with the leading term. We consider an information stream with M_i-level PSK modulation, where the source emits waves, the PSK information modulation is accomplished upon interaction with the metasurface, and the waves are directed to the desired receivers. We stress that it is not the source but the metasurface that performs the PSK modulation. The list of possible desired phases at the ith receiver (located at $\boldsymbol{r}_i$) is

$$\phi_i \in \theta_i + \left\{0, \frac{2\pi}{M_i}, 2\frac{2\pi}{M_i}, \ldots, (M_i-1)\frac{2\pi}{M_i}\right\}, \quad i = 1, 2, \ldots, Q,$$

where the symbol θ_i denotes the phase bias for the ith receiver.

We here consider a realistic scenario, where any two receivers are well separated in terms of the Rayleigh limit, $|A_1^{\text{SISO}}(\boldsymbol{r}_i, \boldsymbol{r}_s; q, s)| \approx 0$ for $i \neq q$. Then, as detailed in Appendix E, we can obtain the coherence of $\widehat{\mathcal{H}}_{\text{SIMO}}(\boldsymbol{r}_i, \boldsymbol{r}_s; \{q\}, s)$ and $\widehat{\mathcal{H}}_{\text{SIMO}}(\boldsymbol{r}_j, \boldsymbol{r}_s; \{q\}, s)$:

$$\begin{aligned}
&\left\langle \widehat{\mathcal{H}}_{\text{SIMO}}(\boldsymbol{r}_i, \boldsymbol{r}_s; \{q\}, s), \widehat{\mathcal{H}}_{\text{SIMO}}(\boldsymbol{r}_j, \boldsymbol{r}_s; \{q\}, s) \right\rangle \\
&= B_0^{\text{SIMO}} A_0 \sum_{n_{p:1\to Q/n_i}} Z^*_{\{M_p n_p \theta_p\}} E^{\text{SIMO},*}_{\{M_p n_p\}}(\boldsymbol{r}_j; \{q\}, s) \\
&\quad + B_0^{\text{SIMO},*} A_0^* \sum_{n_{p:1\to Q/n_j}} Z_{\{M_p n_p \theta_p\}} E^{\text{SIMO}}_{\{M_p n_p\}}(\boldsymbol{r}_i; \{q\}, s), \quad \text{for } i \neq j,
\end{aligned} \tag{9a}$$

$$\left\langle \left| \widehat{\mathcal{H}}_{\text{SIMO}}(\boldsymbol{r}_i, \boldsymbol{r}_s; \{q\}, s) \right|^2 \right\rangle \approx \left| B_0^{\text{SIMO}} A_0 \right|^2, \tag{9b}$$

where $Z_{\{p_q \theta_q\}} = \exp(\mathrm{j} \sum_q p_q \theta_q)$, and we have assumed that $A_0 \approx A_1^{\text{SISO}}(\boldsymbol{r}_i, \boldsymbol{r}_s; i, s)$ holds for any $\boldsymbol{r}_i \in \{q\}$ when the receivers are in a relative small range. Moreover, the superscript symbol $*$ denotes the complex conjugate operation. We can observe that the coherence function depends on the choice of the phase bias $\{\theta_i\}$, implying that the quantization-related signal interference can be improved by optimizing the setting of the phase bias $\{\theta_i\}$. This observation is consistent with the results presented at the end of this section in the context of holography.

To rigorously evaluate additional signal interference originating from the one-bit quantization of the metasurface, we now examine the statistical behavior of a given digital information symbol transferred through a given wireless SIMO channel while simultaneously the remaining SIMO links are deployed for other (statistically independent) digital information streams. For the digital information symbol acquired at $\boldsymbol{r}_u$, the statistical mean $\mu_u^{\text{SIMO}} = \langle \widehat{\mathcal{H}}_{\text{SIMO}}(\boldsymbol{r}_u, \boldsymbol{r}_s; \{q\}, s) \rangle$ and variance $\sigma_u^{\text{SIMO}} =$

$\langle|\widehat{\mathcal{H}}_{\mathrm{SIMO}}(\boldsymbol{r}_u,\boldsymbol{r}_s;\{q\},s)-\langle\widehat{\mathcal{H}}_{\mathrm{SIMO}}(\boldsymbol{r}_u,\boldsymbol{r}_s;\{q\},s)\rangle|^2\rangle$ are readily derived as

$$\mu_u^{\mathrm{SIMO}}=B_0^{\mathrm{SIMO}}\underbrace{A_1^{\mathrm{SISO}}(\boldsymbol{r}_u,\boldsymbol{r}_s;u,s)\exp(\mathrm{j}\phi_u)}_{\text{for continuous coding metasurface}}$$
$$+\underbrace{\sum_{\{p_q\}/\{\Sigma_q|p_q|=1\&p_q\neq-1\}}E_{\{p_q\}}^{\mathrm{SIMO}}(\boldsymbol{r}_u,\boldsymbol{r}_s;\{q\},s)\exp[\mathrm{j}p_u\phi_u]Z_{\{p_q\theta_q\}/p_u\theta_u}\prod_{q=1,q\neq u}^{Q}\delta_{p_q-n_qM_q}}_{\text{one-bit quantization mean bias}}, \tag{10a}$$

$$\sigma_u^{\mathrm{SIMO}}=\underbrace{\left|B_0^{\mathrm{SIMO}}\right|^2\sum_{q=1,q\neq u}^{Q}\sigma_q^2\left\lfloor A_1^{\mathrm{SISO}}(\boldsymbol{r}_u,\boldsymbol{r}_s;q,s)\right\rfloor^2}_{\text{for continuous coding metasurface}}+\underbrace{\chi(u,\{M_q\})}_{\text{one-bit quantization variance}}, \tag{10b}$$

where $Z_{\{p_q\theta_q\}/p_u\theta_u}=\exp(\mathrm{j}\sum_{q,q\neq u}p_q\theta_q)$, σ_q^2 is the covariance of the intended information stream of the qth receiver. In addition, the factor $\chi(u,\{M_q\})$ characterizes the signal interferences arising from the one-bit quantization of the coding metasurface, see Appendix F. Furthermore, for the whole SIMO system, the variance can be approximated by taking average of $\{\sigma_u^{\mathrm{SIMO}}\}$ over all intended receivers. As a result, we have

$$\begin{aligned}\sigma_{\mathrm{SIMO}}^2&=\frac{1}{Q}\sum_{u=1}^{Q}\sigma_u^{\mathrm{SIMO}}\\&=\left|B_0^{\mathrm{SIMO}}\right|^2\underbrace{\frac{1}{Q}\sum_{u=1}^{Q}\sum_{q=1,q\neq u}^{Q}\sigma_q^2\left\lfloor A_1^{\mathrm{SISO}}(\boldsymbol{r}_u,\boldsymbol{r}_s;q,s)\right\rfloor^2}_{\sigma_{\mathrm{cont}}^2}+\underbrace{\frac{1}{Q}\sum_{u=1}^{Q}\chi(u,\{M_q\})}_{\chi}.\end{aligned} \tag{11}$$

If an continuous coding metasurface is used instead, variance and mean are characterized by σ_{cont}^2 and $A_1^{\mathrm{SISO}}(\boldsymbol{r}_u;u,s)\exp(\mathrm{j}\phi_u)$. Therefore, the effect of the one-bit quantization of the metasurface is obvious from (10): the one-bit quantization induced mean bias as well as the additional noise due to the one-bit quantization variance both reduce the distinguishability of distinct information symbols.

4 Difference in information capacity of one-bit vs. ideal metasurface

In this section, based on the above-established results, we investigate the relation between the information capacities of a metasurface with one-bit coding and a metasurface with continuous coding. Based on Shannon's theory, the information capacity $\mathcal{C}_{\mathrm{cont}}$ of an continuous coding metasurface can be readily obtained [53,54]. For instance, for the SIMO case, it reads $\mathcal{C}_{\mathrm{cont}}=Q\log_2(1+S/(\sigma_n^2+\sigma_{\mathrm{cont}}^2))$ per frequency, where S and σ_n^2 denote the signal and system noise levels, respectively, and $S=\mathcal{P}|A_1^{\mathrm{SISO}}(\boldsymbol{r}_q,\boldsymbol{r}_s;q,s)|^2\approx\mathcal{P}|MN/r_sr_q|^2$ (far-field approximation). The one-bit quantization of the metasurface has two consequences: (i) an energy loss by a factor of $\gamma_{\text{one-bit}}^2$, and (ii) additional noise $\sigma_{\text{one-bit}}^2$. Both effects deteriorate the SNR (signal-to-noise ratio) and thereby reduce the information capacity in the case of the one-bit coding metasurface:

$$\mathcal{C}_{\text{one-bit}}\approx Q\log_2\left(1+\gamma_{\text{one-bit}}^2S/\left(\sigma_n^2+\sigma_{\text{one-bit}}^2\right)\right), \tag{12}$$

where

$$\gamma_{\text{one-bit}}=\begin{cases}B_1^{\mathrm{SISO}}, & \text{for SISO},\\ B_1^{\mathrm{SIMO}}, & \text{for SIMO},\\ B_1^{\mathrm{MIMO}}, & \text{for MIMO},\end{cases}\quad\text{and}\quad\sigma_{\text{one-bit}}^2=\begin{cases}0, & \text{for SISO},\\ \sigma_{\mathrm{SIMO}}^2, & \text{for SIMO},\\ \sigma_{\mathrm{MIMO}}^2, & \text{for MIMO}.\end{cases}$$

The approximate-equal symbol in (12) is used because the one-bit quantization mean bias in (11) decreases the distinguishable distance between two different information symbols, which will decrease the achievable information capacity. Now, taking the SIMO as an illustrative example, we can derive the relation between $\mathcal{C}_{\mathrm{cont}}$ and $\mathcal{C}_{\text{one-bit}}$ as

$$\frac{\Delta\mathcal{C}}{Q}=\frac{C_{\text{one-bit}}-C_{\mathrm{cont}}}{Q}\approx\log_2\left(\gamma_{\text{one-bit}}^2\frac{\sigma_n^2+\sigma_{\mathrm{cont}}^2}{\sigma_n^2+\sigma_{\text{one-bit}}^2}\right)\approx\log_2\left(\gamma_{\text{one-bit}}^2\frac{\sigma_n^2+\sigma_{\mathrm{cont}}^2}{\sigma_n^2+\gamma_{\text{one-bit}}^2\sigma_{\mathrm{cont}}^2+\chi}\right), \tag{13}$$

where we assumed SNR $\gg 1$ and $\sigma^2_{\text{one-bit}} = \gamma^2_{\text{one-bit}}\sigma^2_{\text{cont}} + \chi$ in (13), respectively. Note that the definition in (13) implies $\Delta\mathcal{C} \leqslant 0$. Considering that $\frac{\Delta\mathcal{C}}{Q}$ behaviors as a monotone decreasing function of σ^2_n for $\sigma^2_{\text{cont}} > \sigma^2_{\text{one-bit}}$, we can estimate its lower and upper bounds:

$$\log_2\left(\gamma^2_{\text{one-bit}}\right) \leqslant \frac{\Delta\mathcal{C}}{Q} \leqslant \log_2\left(\frac{\gamma^2_{\text{one-bit}}\sigma^2_{\text{cont}}}{\gamma^2_{\text{one-bit}}\sigma^2_{\text{cont}} + \chi}\right). \tag{14}$$

The upper bound of $\frac{\Delta\mathcal{C}}{Q}$ is reached when the system noise level σ^2_n is relatively low $\left(\sigma^2_n \ll \sigma^2_{\text{cont}}\right.$ and $\left.\sigma^2_n \ll \gamma^2_{\text{one-bit}}\sigma^2_{\text{cont}} + \chi\right)$. Furthermore, if $\chi \ll \gamma^2_{\text{one-bit}}\sigma^2_{\text{cont}}$, the upper bound approaches to zero, i.e., $\frac{\Delta C}{Q} \to 0$, which implies that the one-bit coding metasurface has nearly the same information capacity as the continuous metasurface under these conditions. We will see that the inequality $\chi \ll \gamma^2_{\text{one-bit}}\sigma^2_{\text{cont}}$ holds when the number of channels Q is small and lowlevel PSK is used. In this case, the adverse effect of lower signal intensity due to one-bit coding is counterbalanced by a lower signal interference.

5 Results and discussion

5.1 Information-encoding capabilities of one-bit coding metasurface

We consider the SISO case, and systematically study the information-encoding capabilities of the one-bit coding metasurface in wireless communications with M_q-level PSK, which can ideally achieve the phase quantization of $\widehat{\mathcal{H}}_{\text{SISO}}$ as $\phi_q \in \{\frac{2\pi(i-1)}{M_q}, i = 1, 2, \ldots, M_q\}$. To quantify to what extent the one-bit coding metasurface is capable of approaching these desired values, we define the following metric for the achievable phase resolution:

$$\Delta\varphi_{\text{SISO}}\left(\boldsymbol{r}_q\right) = \min_{i,j}\left|\varphi^{(i)}_{\text{SISO}}\left(\boldsymbol{r}_q\right) - \varphi^{(j)}_{\text{SISO}}\left(\boldsymbol{r}_q\right)\right|, \tag{15}$$

where $\varphi^{(i)}_{\text{SISO}}$ is the phase of $\widehat{\mathcal{H}}_{\text{SISO}}$ for the ith intended phase. To quantify the difference between the performance with one-bit and ideal coding, we define the following metric:

$$\text{EC}^{\text{SISO}} = \frac{1}{MN}\sum_{m,n}\left|\text{sign}\left[\cos\left(\tilde{\phi}^{\text{SISO}}_{nm}\right)\right] - \cos\left(\tilde{\phi}^{\text{SISO}}_{nm}\right)\right|. \tag{16}$$

Figures 3(a) and (e) plot the dependence of $\Delta\varphi_{\text{SISO}}\left(\boldsymbol{r}_q\right)$ and EC^{SISO}, respectively, on $\boldsymbol{r}_q$ for quad-phase shift keyed (QPSK) ($M_q = 4$) with a normally incident source deployed at a distance of 2 km from metasurface, i.e., in its far-field. The ability of the one-bit coding metasurface to perform QPSK information encoding with high fidelity is immediately obvious, except for the case when the receiver is on the azimuth 0° and in the far-field region. This result is in line with our above-mentioned interpretation of (6). In a scenario with a source incident at an oblique angle, as shown in Figures 3(d) and (f), there appears to be a similar limitation if $\hat{\boldsymbol{r}}_q + \hat{\boldsymbol{r}}_s \| \widehat{\boldsymbol{n}}$. Indeed, in this case the far-field approximation of $\tilde{\phi}^{\text{SISO}}_{nm}$ reads

$$\begin{aligned}\tilde{\phi}^{\text{SISO}}_{nm} &= k\left(\left|\boldsymbol{r}_s - \boldsymbol{r}_{m,n}\right| + \left|\boldsymbol{r}_q - \boldsymbol{r}_{m,n}\right|\right) + \phi_q \approx k\left(r_s + r_q - \boldsymbol{r}_{m,n}\cdot\left(\hat{\boldsymbol{r}}_s + \hat{\boldsymbol{r}}_q\right)\right) + \phi_q \\ &\approx k\left(r_s + r_q\right) + \phi_q, \quad \text{for } \hat{\boldsymbol{r}}_q + \hat{\boldsymbol{r}}_s \| \hat{\boldsymbol{n}},\end{aligned} \tag{17}$$

such that the control coding pattern of the one-bit coding programmable metasurface is $\mathcal{C}^{\text{SISO}}_{m,n} = \text{sign}\left[\cos\left(k\left(r_s + r_q\right) + \phi_q\right)\right]$. Again, it is obvious why a receiver in the far field with $\hat{\boldsymbol{r}}_q + \hat{\boldsymbol{r}}_s \| \widehat{\boldsymbol{n}}$ cannot distinguish M_q-level PSK information if $M_q > 2$. In such cases, PSK must be limited to $M_q = 2$ (BPSK). The pronounced increase of EC^{SISO} for this scenario in Figures 3(e) and (h) further confirms that this limitation is attributed to the one-bit coding of the programmable metasurface.

Higher-order PSKs with $M_q = 8$ and $M_q = 16$ are considered in Figures 3(b) and (c) and Figures 3(f) and (g) in terms of $\Delta\varphi_{\text{SISO}}\left(\boldsymbol{r}_q\right)$ and EC^{SISO}, respectively. In light of the well-known reciprocal property [55], we conclude that the one-bit coding metasurface is capable of efficiently manipulating the EM information at least up to 16-level PSK in the considered setup, if the source and receiver are deployed in the near-field region (see Appendix G). In general, efficient manipulation of EM information becomes increasingly challenging as M_q increases due to the increasing importance of unwanted parasitic beams.

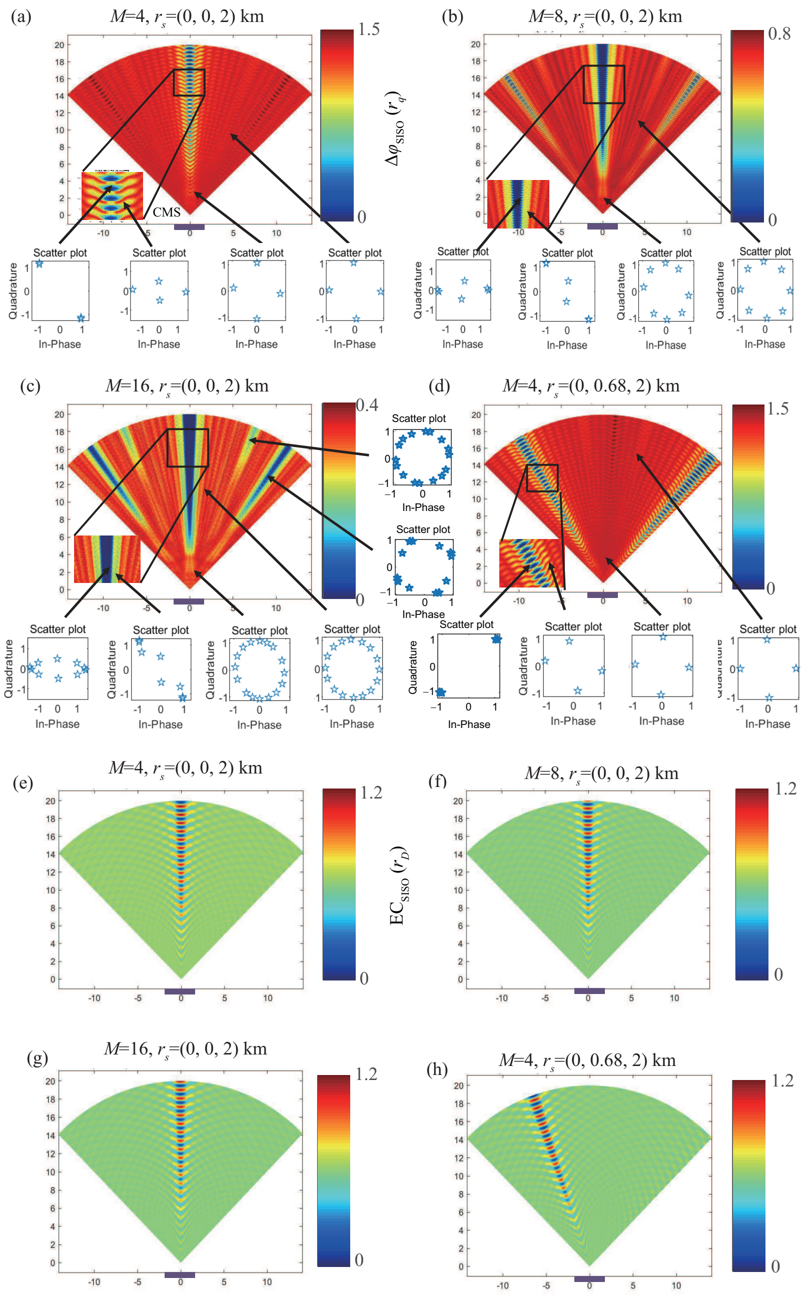

Figure 3 (Color online) M-level PSK with a one-bit coding programmable metasurface in SISO. (a)–(d) Dependence of phase resolution $\Delta\varphi_{\rm SISO}$ on the receiver's location $\boldsymbol{r}_q$. Considering receiver locations are within a distance between 0 and 20 m from the metasurface for an azimuth between -45° and 45°. The insets provide representative constellation diagrams. Different levels of PSK and source location are considered, as indicated in the subfigure titles. (e)–(h) Dependence of $\mathrm{EC}^{\rm SISO}$ on $\boldsymbol{r}_q$ for the same settings as in (a)–(d). In addition, the metasurface has been marked with a yellow solid rectangular.

Throughout our paper, we have assumed an 'ideal' one-bit quantization of the programmable metasurface. Specifically, we assumed that upon switching the meta-atom from its '0' (or '1') state to its '1' (or '0') state, the reflection phase experiences a change of 180° while the reflection amplitude remains unchanged. However, such ideal one-bit quantization cannot be realized in practice for many reasons, including non-ideal active lumped elements (e.g., the PIN diode) and fabrication errors. The reflection response of the non-ideal one-bit meta-atom is $A_+e^{j\phi_+}$ and $A_-e^{j\phi_-}$ for states '1' and '0' (with $0 \leqslant A_\pm \leqslant 1$), respectively, instead of 1 and -1. The methodology developed in our paper can be readily generalized to non-ideal one-bit meta-atoms. Specifically, the radiation signal for the non-ideal one-bit quantization

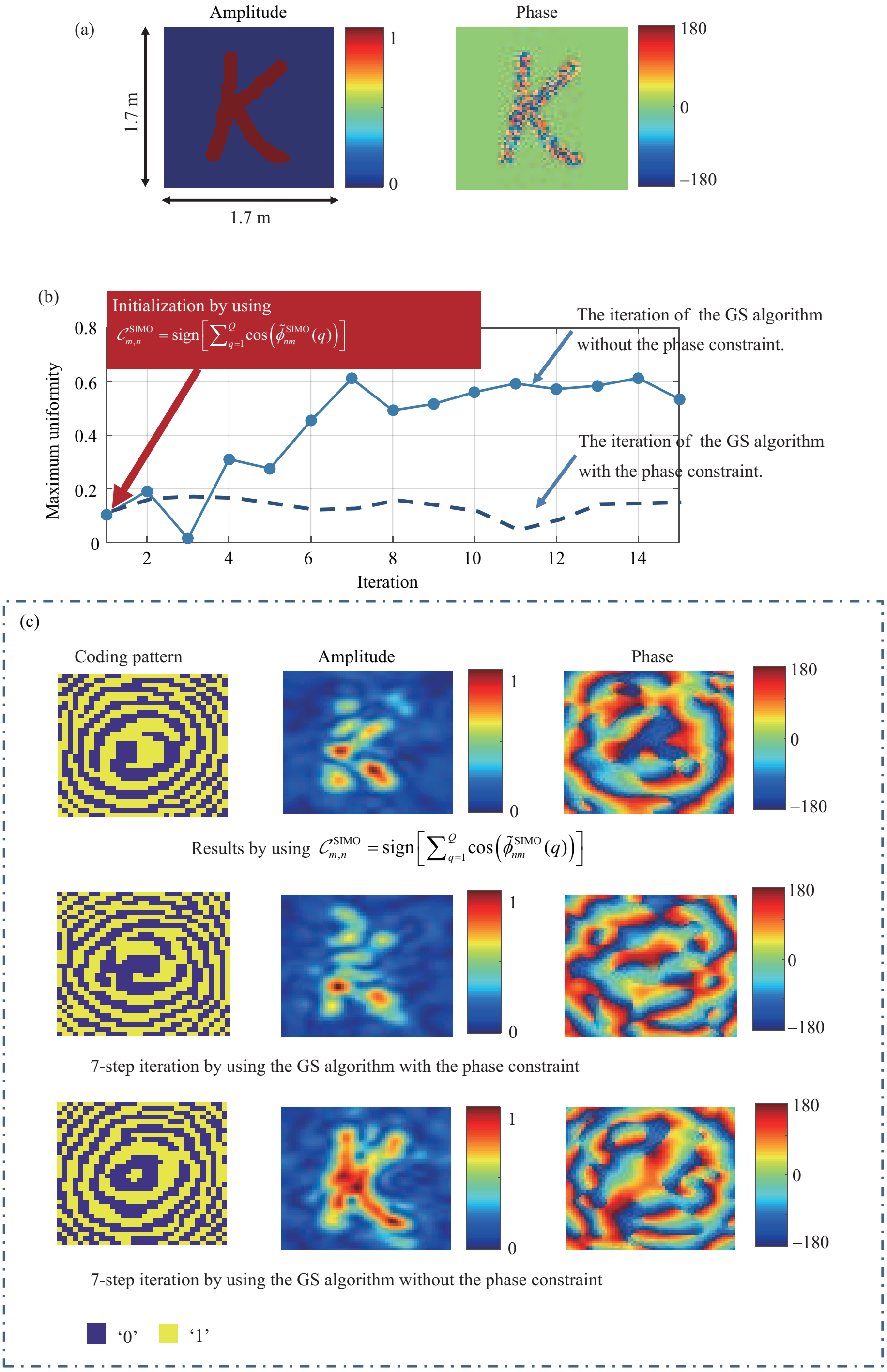

Figure 4 (Color online) SIMO results for holographic imaging. The source is deployed at $(0,0,2)$ m and the observation plane is at a distance of 3 m from the one-bit coding metasurface. (a) Amplitude (left) and phase (right) of the targeted hologram to be generated by the one-bit coding metasurface. (b) Convergence of the GS algorithm with and without the phase constraint in terms of the maximum uniformity as figure of merit (see Eq. (1) in [56]). In both cases, the GS algorithm is initialized with $\mathcal{C}_{m,n}^{\mathrm{SIMO}} = \mathrm{sign}[\sum_{q=1}^{Q}\cos(\tilde{\phi}_{nm}^{\mathrm{SIMO}}(q))]$. (c) Results using $\mathcal{C}_{m,n}^{\mathrm{SIMO}}$ and Eq. (2) are shown in the top row, where the coding pattern of the one-bit metasurface, the amplitude and phase of the holographic image are shown on the left, middle and right, respectively. The corresponding results using the GS algorithm with and without the phase constraint are shown in the middle and bottom rows, respectively.

$\widehat{\mathcal{H}}_{\mathrm{SISO,SIMO,MIMO}}^{\text{non-ideal}}(\boldsymbol{r};\cdots)$ is

$$\widehat{\mathcal{H}}_{\mathrm{SISO,SIMO,MIMO}}^{\mathrm{non}}(\boldsymbol{r};\cdots) = \gamma_0 A_0^{\mathrm{SISO}}(\boldsymbol{r};q\cdots) + \gamma_1 \widehat{\mathcal{H}}_{\mathrm{SISO,SIMO,MIMO}}(\boldsymbol{r};\cdots), \tag{18}$$

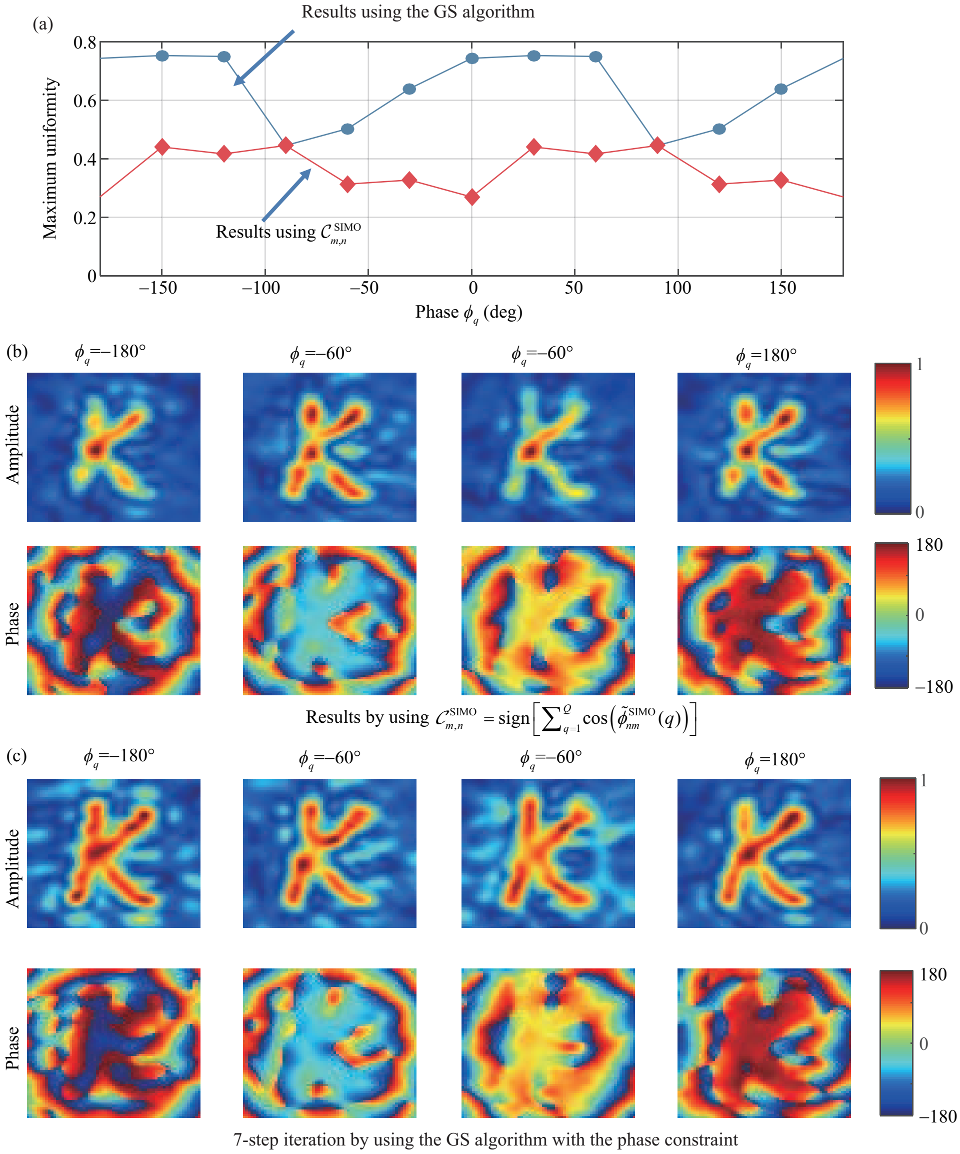

Figure 5 (Color online) Relaxing phase constraints in the SIMO holography. The setup is the same as that in Figure 4 except that the phase of targeted holographic image is set to be constant rather than random. (a) Image quality (evaluated in terms of the maximum uniformity) as a function of the targeted phase. (b) Results with $\mathcal{C}_{m,n}^{\rm SIMO}$ and Eq. (7) in terms of normalized amplitude and phase of the obtained holographic image. (c) The corresponding results by the GS algorithm with the phase constraint.

where $\gamma_0 = \frac{(A_+ {\rm e}^{{\rm j}\phi_+} + A_- {\rm e}^{{\rm j}\phi_-})}{2}$ and $\gamma_1 = \frac{(A_+ {\rm e}^{{\rm j}\phi_+} - A_- {\rm e}^{{\rm j}\phi_-})}{2}$. It can be observed from (18) that, in terms of manipulating the radiation beam, the non-ideality of a one-bit quantized metasurface results in additional energy leakage. More discussion about the non-ideal one-bit quantization of programmable coding metasurfaces can be found in Appendix I.

5.2 Signal interference of one-bit coding metasurface

To illustrate the results and conclusion on signal interference, we consider a concrete and promising SIMO application: metasurface-generated holograms [32]. Specifically, we examine the capability of the one-bit coding metasurface to realize the holographic image of English letter 'K'.

We assume that the desired phases over the profile of the letter 'K' are randomly distributed, as shown in Figure 4(a). The normalized amplitude and phase of the achieved holographic image at a distance of 3 m away from the one-bit coding metasurface are shown in the top row of Figure 4(c), and the corresponding control coding pattern of the one-bit coding metasurface is reported. For comparison, the corresponding results obtained by the GS algorithm with and without the phase constraint are

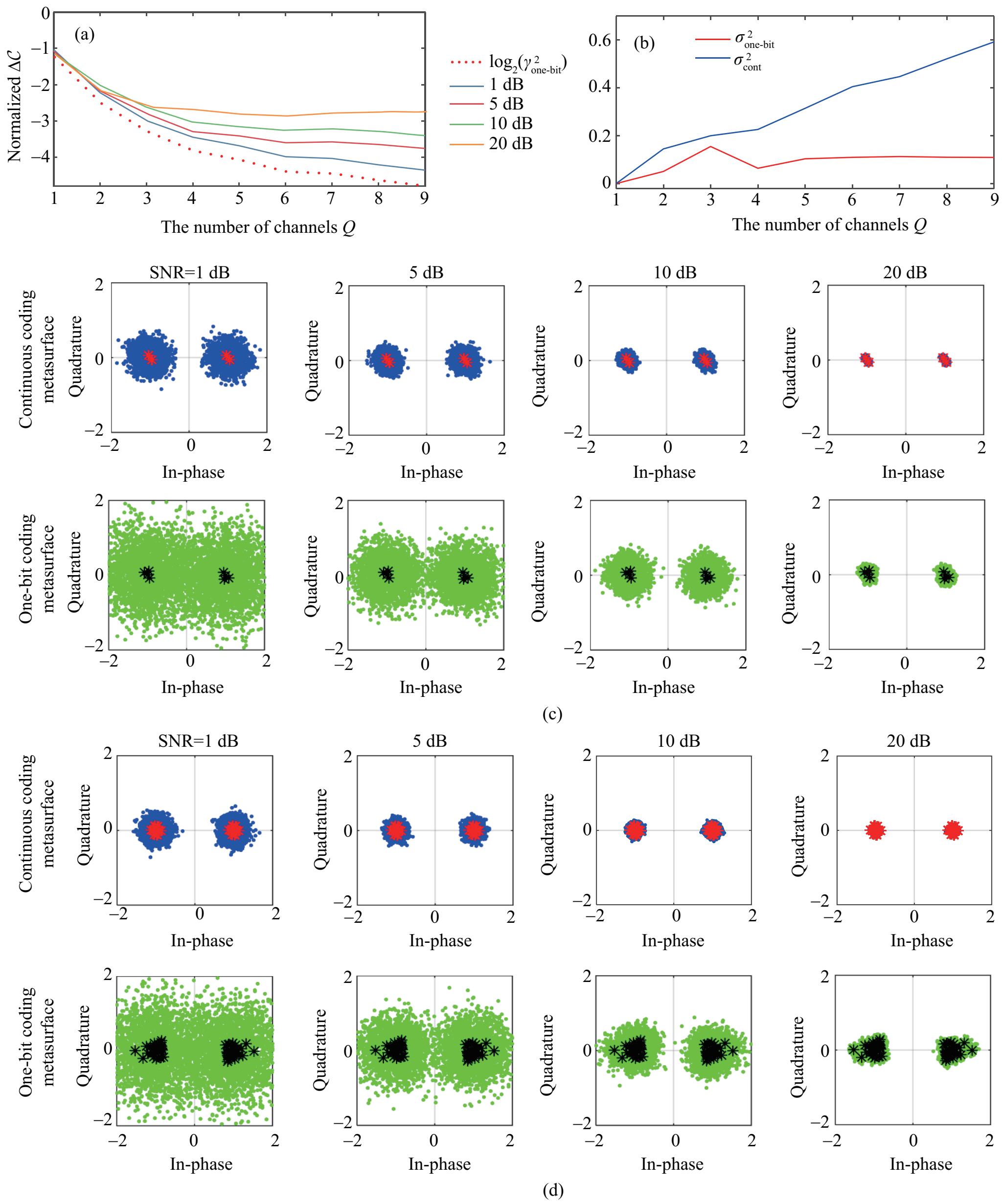

Figure 6 (Color online) (a) The normalized difference information capacity $\frac{\Delta c}{Q}$ in SIMO setting, in comparing the one-bit coding metasurface with the continuous metasurface in the SIMO scenario as a function of Q for different system SNRs when the receiver and source are in the near-field region of the metasurface. For comparison, the lower bound of $\frac{\Delta C}{Q}$ represented by $\log_2(\gamma^2_{\text{one-bit}})$ is also plotted. The binary PSK ($M = 2$) is considered. (b) The comparison of $\sigma^2_{\text{one-bit}}$ and σ^2_{cont} as a function of the number of channels Q. (c) and (d) Constellation diagrams for $Q = 3$ and $Q = 6$ for different system SNRs. The constellation diagram axes are normalized by B_0^{SIMO}. Additionally, the red-marked and black-marked stars of the constellation diagrams characterize the signal interferences for the system-noise-free case, respectively. In this set of examinations, the source is located at $(0, 0, 1.2)$ m, and the receivers are deployed at the distance of 3 m away from the metasurface.

shown in the middle and bottom rows of Figure 4(c). In both cases we initialize the GS algorithm with $\mathcal{C}^{\text{SIMO}}_{m,n}$. The convergence behavior of the GS algorithm with and without the phase constraint is plotted in Figure 4(b) [56]. Our results show that the proposed closed-form formula for obtaining the coding pattern of the one-bit coding metasurface, $\mathcal{C}^{\text{SIMO}}_{m,n}$, gives satisfactory results with comparable quality to that achieved by the iterative GS algorithm. In both cases, the quantization-induced signal interference among different channels notably limits the quality of the holographic image. If the constraints are relaxed by ignoring the desired phases, the one-bit coding metasurface yields a holographic image of acceptable quality. A further possibility is to simplify the phase constraint by targeting a constant value for the entire letter 'K'. The corresponding results in Figure 5 for different targeted phase values reveal a setting, in which the one-bit coding metasurface produces acceptable holographic images in terms of both phase and amplitude. Then, it can be verified that the phase $\{\phi_q\}$ could provide controllable parameters to minimize the signal interference, as pointed out previously with respect to the phase bias $\{\theta_i\}$.

5.3 Information capability of one-bit and continuous coding metasurfaces

We go on to evaluate the normalized difference in information capacities $\frac{\Delta\mathcal{C}}{Q}$ of the one-bit and continuous coding metasurfaces in the SIMO scenario. Figure 6(a) plots $\frac{\Delta\mathcal{C}}{Q}$ as a function of the number of channels Q for different system SNRs, and Figure 6(b) compares $\sigma^2_{\text{one-bit}}$ and σ^2_{cont} as a function of the number of channels Q, in which the source and receivers are deployed in the near-field region of the metasurface. It can be verified from this set of figures that $\frac{\Delta\mathcal{C}}{Q}$ approaches to the upper bound identified in (16), and that the upper bound will tend to zero, as the system SNR is increased; in contrast, for low system SNRs, the lower bound $\log_2(\gamma^2_{\text{one-bit}})$ is approached. Some representative constellation diagrams for $Q=3$ and $Q=6$ for different system SNRs are shown in Figures 6(c) and (d), in which the red and black stars characterize the signal interferences for the system-noise-free case, respectively. Additionally, the bit-error analysis on the system of one-bit coding metasurface can be made along the same line, as detailed in Appendix H. It is obvious, in line with our previous calculations, that the one-bit quantization of the metasurface will give rise to additional signal interferences, and that such interferences will become stronger if the number of channels Q is larger. Nonetheless, it can be observed that the one-bit coding programmable metasurface performs almost as well as the continuous coding metasurface as long as Q is not too large.

6 Conclusion

We have explored fundamental limitations of the one-bit coding metasurfaces in comparison to the continuous coding metasurfaces in terms of their information capacity and considered illustrative examples from key applications in wireless communications and holography. Our results illustrate surprisingly nearly no performance deterioration due to the one-bit coding under mildly favorable constraints, such as low-level PSK, few-user SIMO or relaxed phase constraints on hologram. We expect that these fundamental insights will impact a wide range of metasurface-assisted techniques seeking to control the flow of information, both for electromagnetic waves and other frequencies and wave phenomena [45–52]. Looking forward, an avenue for the future research is to generalize the presented concepts to scattering rich environments [18, 20, 24] in which the scattering and reverberation will make the identification of suitable metasurface configurations more challenging; however, these seemingly adverse scattering effects can be leveraged as secondary sources that may further reduce the performance gap between the one-bit and continuous coding of the programmable metaatoms.

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Supporting information Appendixes A–I. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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