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**Abstract**

The use of terahertz (THz) wave for absolute positioning has recently been demonstrated in [1]–[4] for the sake of contactless sensing, operation in adversarial conditions (e.g., fire, smoke), and robustness to dust and dirt. THz absolute positioning can operate in a raster [1], [2] or compressed scanning mode [3], [4]. In the raster scanning mode of Fig. 1 (a), the scale with THz-band QR patterns is illuminated by a single THz transceiver, and a programmable mechanical raster moves the transceiver in one or two dimensions. In the compressed scanning mode of Fig. 1 (b), the THz positioning system also uses a single THz transceiver but with random masks and collimating/focusing lens to cover a large area (versus a single pixel in the raster scanning) of the scale encoded by QR patterns which can be uniquely mapped to positions. Consequently, signal processing algorithms are required to detangle the compressed THz signal and recover the underlying QR pattern due to the mixing between random masks and QR patterns. In [3], [4], we proposed a variational Bayesian inference (VBI) method for this task by exploiting the non-negative and binary features of THz reflectance. This paper aims to report the first experimental result to verify the THz QR positioning in the compressed scanning mode.

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# Terahertz QR Positioning: Experimental Results

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***Abstract*—This paper reports the first experimental result on THz-band absolute positioning on two-dimensional binary pseudo-random reflectance patterns or, equivalently, QR codes, in a compressed scanning mode.**

## I. Introduction

The use of terahertz (THz) wave for absolute positioning has recently been demonstrated in [1]–[4] for the sake of contactless sensing, operation in adversarial conditions (e.g., fire, smoke), and robustness to dust and dirt. THz absolute positioning can operate in a *raster* [1], [2] or *compressed* scanning mode [3], [4]. In the raster scanning mode of Fig. 1 (a), the scale with THz-band QR patterns is illuminated by a single THz transceiver, and a programmable mechanical raster moves the transceiver in one or two dimensions.

In the compressed scanning mode of Fig. 1 (b), the THz positioning system also uses a single THz transceiver but with random masks and collimating/focusing lens to cover a large area (versus a single pixel in the raster scanning) of the scale encoded by QR patterns which can be uniquely mapped to positions. Consequently, signal processing algorithms are required to detangle the compressed THz signal and recover the underlying QR pattern due to the mixing between random masks and QR patterns. In [3], [4], we proposed a variational Bayesian inference (VBI) method for this task by exploiting the *non-negative* and *binary* features of THz reflectance. This paper aims to report the first experimental result to verify the THz QR positioning in the compressed scanning mode.

## II. Signal Model

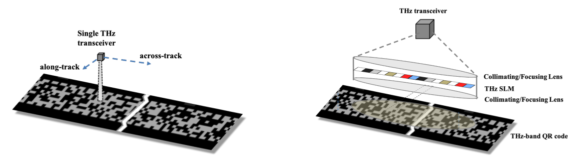
Let $\boldsymbol{x} = [x_1, \cdots, x_N]^T$, $x_n \in \{\mu_1, \cdots, \mu_K\}$ denote the 1D or 2D pseudo-random position pattern to be recovered from $M$ compressed measurements $\boldsymbol{y} = [y_1, \cdots, y_M]^T$

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{v}, \tag{1}$$

where each row of $\boldsymbol{A}$ represents a random mask at the THz band, $\boldsymbol{v} = [v_1, \cdots, v_M]^T$ is the Gaussian noise with zero mean and variance $\beta^{-1}$. In the case of binary position coding, $K = 2$ with $\mu_1 = 0$ and $\mu_2 = 1$. As shown in [3] and [4], we assume a hierarchical prior model on $x_n$

$$\mathbb{P}\left(x_n | \boldsymbol{\alpha}_n, \boldsymbol{C}_n; \boldsymbol{u}\right) = \prod_{i=1}^{K} \mathcal{N}_+\left(x_n; \mu_i, \alpha_{n,i}^{-1}\right)^{C_{n,i}}, \tag{2}$$

where $\boldsymbol{C}_n = [C_{n,1}, \cdots, C_{n,K}]$ is a label vector with only one non-zero element assigning one of the $K$ truncated Gaussian




(a) (b)

Fig. 1. THz positioning in a) raster and b) compressed scanning modes.

components to $x_n$ and

$$\mathcal{N}_+\left(x_n; \mu, \alpha^{-1}\right) = \begin{cases} \eta^{-1}\sqrt{\frac{\alpha}{2\pi}} e^{-\frac{\alpha(x-\mu)^2}{2}} & x \geq 0, \\ 0, & x < 0, \end{cases} \tag{3}$$

with $\eta = 1 - \Phi\left(-\mu\sqrt{\alpha}\right)$ denoting the normalization factor and $\Phi\left(\cdot\right)$ denoting the cumulative distribution function of the standard normal distribution. Moreover, we further assume that the label variable $\boldsymbol{C}_n$ follows the categorical distribution or generalized Bernoulli distribution $\mathbb{P}\left(\boldsymbol{C}_n; \boldsymbol{\pi}\right) = \prod_{i=1}^{K} \pi_i^{C_{n,i}}$ with event probabilities $\boldsymbol{\pi} = [\pi_1, \cdots, \pi_K]$ where $\sum_{i=1}^{K} \pi_i = 1$.

Finally, we assume the Gamma distribution for $\boldsymbol{\alpha}_{n,i}$, i.e., $\mathbb{P}\left(\boldsymbol{\alpha} | a; b\right) = \prod_{i=1}^{K} \prod_{n=1}^{N} \text{Gamma}\left(\alpha_{n,i} | a, b\right)$ with $a = b = 10^{-6}$.

## III. Position Recovery: A Quick Overview

As detailed in [3] and [4], we provide a quick overview of the position recovery algorithm based on the above signal model. The idea is to use the variational Bayesian framework to approximate the posterior distributions of all hidden variables $\{\boldsymbol{x}, \boldsymbol{\alpha}, \boldsymbol{C}\}$ in the above signal model, and update other deterministic model parameters such as the noise variance $\beta^{-1}$ and the alphabet $\{\mu_i\}_{i=1}^{K}$ if they are unknown or perturbed.

*The element-wise position pattern* $\{x_n\}_{n=1}^{N}$ follows an independent truncated Gaussian posterior distribution,

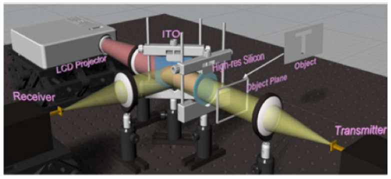
$$q\left(x_n\right) = \begin{cases} \phi_n^{-1} \frac{1}{\sqrt{2\pi}\tilde{\sigma}_n} \exp\left(-\frac{(x_n - \tilde{\mu}_n)^2}{2\tilde{\sigma}_n^2}\right) & x_n > 0 \\ 0 & x_n \leq 0 \end{cases}, \tag{4}$$

where $\phi_n = 1 - \Phi\left(-\tilde{\mu}_n / \tilde{\sigma}_n\right)$ is the normalization factor.

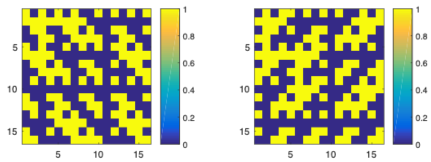
*The label vector* $\boldsymbol{C}$ has the categorical posterior distribution as

$$q\left(C_{n,i}\right) = \prod_{i=1}^{K} \left(\tilde{\pi}_{n,i}\right)^{C_{n,i}} \tag{5}$$

with $\tilde{\pi}_{n,i} = \exp(\gamma_{n,i} - \ln(\sum_{i=1}^{K} \exp(\gamma_{n,i})))$ and $\gamma_{n,i} = -0.5\langle\alpha_{n,i}\rangle\langle(x_n - \mu_i)^2\rangle - \langle\ln \eta_{n,i}\rangle + \ln \pi_i$.




(a)



(b)

Fig. 2. THz positioning experimental system: (a) system configuration; (b) two Hadamard random masks used for mixing.

*The variable* $\boldsymbol{\alpha}$ has the Gamma posterior distribution, i.e.,

$$q\left(\alpha_{n,i}\right) = \text{Gamma}\left(\alpha_{n,i}|\tilde{a}_{n,i}, \tilde{b}_{n,i}\right) \tag{6}$$

with $\tilde{a}_{n,i} = a + 0.5\langle C_{n,i}\rangle$, $\tilde{b}_{n,i} = b + 0.5\langle C_{n,i}\rangle\langle(x_n - \mu_i)^2\rangle$.

*Updating for deterministic parameters* $\{\beta\}$: At each iteration, the noise variance $\beta^{-1}$ can be updated

$$\left(\beta^{-1}\right)^{t+1} = \sum_{m=1}^{M} \left\langle \left(y_m - w_m\right)^2 \right\rangle / M, \tag{7}$$

where $w_m$ is the $m$-th element of $\boldsymbol{w} = \boldsymbol{A}\boldsymbol{x}$.

*An approximate updating rule for* $\{\mu_i\}_{i=1}^{K}$ is given by [3]

$$\mu_i^{t+1} = \frac{\sum_{n=1}^{N} \langle C_{n,i}\rangle \langle \alpha_{n,i}\rangle \langle x_n\rangle}{\sum_{n=1}^{N} \langle C_{n,i}\rangle \langle \alpha_{n,i}\rangle} \tag{8}$$

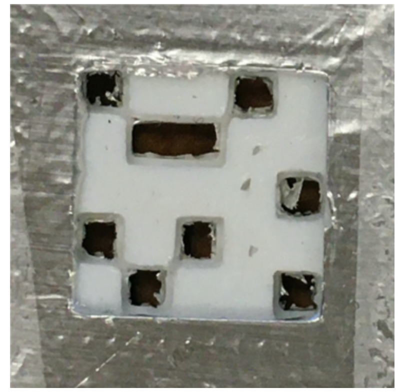
which is the weighted average of the posterior mean of $x_n$ (i.e., $\langle x_n\rangle$) in the corresponding class specified by $C_{n,i}$.

## IV. Experimental THz Positioning

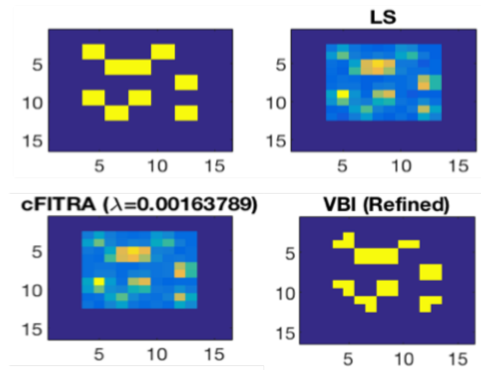
We re-used a single-pixel THz imaging system in [5] with a transmission mode, as shown in Fig.2 (a). The mixing between random masks and QR patterns is realized by a fast spatial light modulator (SLM) implemented via the photoexcitation of a silicon wafer illuminated by visible light from a commercial LCD projector at a refresh rate of 60 Hz. Random Hadamard masks of $16 \times 16$ pixels are generated using two levels of light intensity projected on the high-resistivity silicon wafer. Two of such masks are shown in Fig.2 (b). We adjust the resulting mask area on the wafer surface such that it gives a mask pixel resolution at $1 \times 1$ mm$^2$

We then placed a QR plate sample of Fig.3 (a) in the object plane of Fig.2 (a). The QR plate sample was made of PLA plastic to create binary transmission of 0.3 and 1 in a $6 \times 6$ QR code and wrapped in a metallic (aluminum) foam. The pixel resolution is $2 \times 2$ mm$^2$. Given the mask pixel resolution, we roughly align the mask and QR plate such that each QR pixel is covered by $2 \times 2$ mask pixels.

Given the experiment setup, the equivalent ground truth of the QR plate is shown in the top left plot of Fig.3 (b).



(a)




(b)

Fig. 3. The QR plate: (a) the real sample; (b) recovered QR patterns.

We applied the conventional least square (LS) method, a regularized least square with an $\ell_\infty$ constraint (e.g., FITRA [6] with a regularization parameter of $\lambda \approx 0.00164$), and our VBI method in [3]. Due to the pixel alignments and strong reflections of the foam around the edge, it is seen that the pixels around the edge are difficult to be recovered for all considered methods. By enforcing the binary nature of reflectance, the VBI method provides a much clear recovered QR pattern for the center pixels.

## V. Conclusion

This paper has verified with the compressed scanning over pseudo-random positioning patterns for high-resolution THz absolute positioning using real single-pixel THz imaging systems.

## References

[1] B. Wang, et al., "Metamaterial absorber for THz polarimetric sensing," in *SPIE Photonics West*, 2018.

[2] K. Sadamoto, et al., "Terahertz polarimetric sensing for linear encoder," in *IRMMW-THz 2018*, Sep. 2018.

[3] H. Fu, et al., "Terahertz imaging of binary reflectance with variational Bayesian inference," in *ICASSP 2018*, 2018.

[4] H. Fu, et al., "Terahertz imaging of multi-level pseudo-random reflectance," in *IRMMW-THz 2018*, Sep. 2018.

[5] S. Saqueb and K. Sertel, "Phase-sensitive single-pixel THz imaging using intensity-only measurements," *IEEE Trans. Terahertz Sci. Technol.*, 2016.

[6] C. Studer and E. G. Larsson, "PAR-aware large-scale multi-user MIMO-OFDM downlink," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 2, 2013.