Gopalsami, N.; Liao, S.; Elmer, T.; Heifetz, A.; Raptis, A.C.; , "Compressive sampling in active and passive millimeter-wave imaging," *Infrared, Millimeter and Terahertz Waves (IRMMW-THz), 2011 36th International Conference on* , vol., no., pp.1-2, 2-7 Oct. 2011

doi: 10.1109/irmmw-THz.2011.6105205

Compressive Sampling in Active and Passive Millimeter-Wave Imaging

N. Gopalsami, S. Liao*, T. Elmer, A. Heifetz, and A. C. Raptis
Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL, 60439
* Corresponding author, e-mail: sliao@anl.gov

***Abstract*—We have developed a compressive sampling method based on Hadamard transform for active and passive millimeter wave (mmW) imaging. Hadamard masks of subwavelength sized pixels were used for collecting spatial mmW modulated data with a single-pixel detector system. The image reconstruction from subsampled data was based on a real time, iterative interpolation relaxation technique in the Hadamard space. Compressive sampled active and passive imaging results show that high-fidelity images of objects may be obtained with as small as 1/9 of the data needed for a full set of acquisitions.**

I. Introduction

Compressive sensing (CS) has been recently introduced to reduce the imaging time of single-pixel imaging systems [1]. Exploiting sparsity in the image data, CS technique in principle can be designed to minimize the number of image acquisitions without loss of information in the image. Typical CS-based image collection involves the use of random mask patterns (spatial light modulators) at the image plane which modulate the light intensity at each pixel of the mask depending on the transmissivity/reflectivity assigned to the pixel. The image is reconstructed by inverse transforming the modulated data sets with fewer masks than N, where N is the total number of pixels in the image. Similar to random sampling in CS, imaging based on Hadamard transform have been used in the past for unique reconstruction of the image with a full set (N) of Hadamard acquisitions [2].

In this paper, we apply compressive sampling to single pixel mmW imager in which we used every mth mask in the Hadamard space and reconstructed the image by filling up the missing pixels in the Hadamard space by relaxation interpolation [3]. This approach allows for real-time image reconstruction after each cycle of Hadamard sampling, which can be progressively increased to improve image quality.

II. Results

A. Hadamard Transform and Compressive Sampling

The Hadamard transformed image $\overline{T}$ can be expressed as the weighted sum of image $\overline{I}$ by cyclic matrix S

$$\overline{T} = S \cdot \overline{I} \tag{1}$$

and the original image $\overline{I}$ can be recovered by inverse S transform [2],

$$\overline{I} = S^{-1} \cdot \overline{T} = \frac{2}{pq+1} \; 2S^T + J_{pq} \; \cdot \overline{T} \tag{2}$$

where J is an all-one matrix.

Compressive sampling is achieved by scanning the mask every mth pixel along horizontal and vertical directions. This represents sub–sampled data in the Hadamard transform space. To reconstruct the image, the missing data in the Hadamard space may be calculated with a procedure known as the relaxation method in the electrostatics literature for 2D solution of Poisson equations [3]. It is an iterative scheme where a trial value at a missing pixel may be obtained as the average of the values at the surrounding pixels. Once the missing pixel values are calculated, the reconstruction matrix in Eq. (2) may be used for image reconstruction.

B. Active Imaging

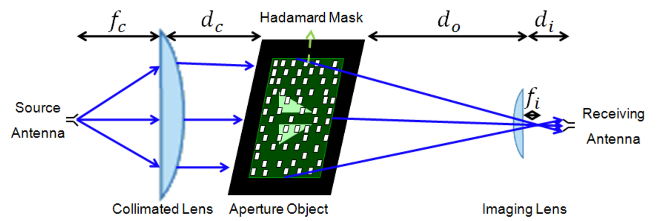

Fig. 1. Schematic diagram of active 94 GHz mmW imaging system using subwavelength Hadamard transform.

Our active 94 GHz mmW imaging system is shown in Fig.1. A circular corrugated antenna is used to launch the mmW radiation and is located at the focal point of a 6.8-inch collimating dielectric lens; the collimated mmW passes through an object aperture on a metal plate 10.0-inch away, which is an equilateral triangle of 1 inch side length with a 3-mm-width metal strip across it; immediately adjacent to the object aperture is an extended 2-dimensional (2D) Hadamard mask shown in Fig. 2, realized by periodically extending a cyclic S-matrix with $p \times q$ pixels ($p = 41$ and $q = p + 2 = 43$: twin-prime construction [2]) to $(2p-1) \times (2q-1)$ or 81-pixel × 85-pixel mask, with a pixel size of $1.27\ \text{mm} \times 1.27\ \text{mm}$, forming a 4.0-inch × 4.2-inch extended mask or a 2.0-inch × 2.1-inch imaging space; the enlarged 2D Hadamard mask is mounted on a 2-axis translation stage, which is used to change the Hadamard patterns. The extended 2D Hadamard is fabricated using chrome coating on a millimeter-wave transparent quartz plate, as shown in Fig. 2.

Fig. 2. An extended Hadamard mask of size 81×85 *pixel fabricated on a quartz plate with chrome coating. A* 41×43 *pixel mask area is exposed for each acquisition.*

Fig. 3 shows the recovered image using full Hadamard transform measurement space. And in Fig. 4, we applied the compressive sampling scheme with $m = 3$, which corresponds to $1/9$ of full acquisitions.

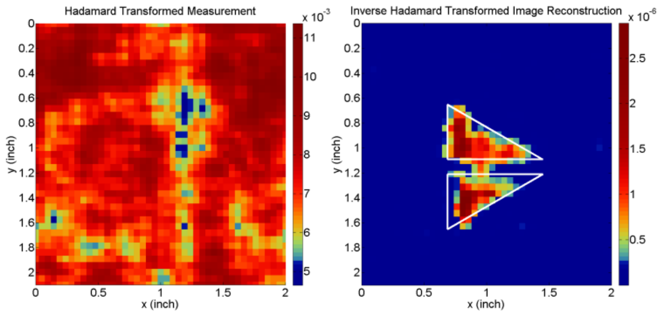

Fig. 3. Left plot: Hadamard transformed measurement; and right plot: inverse Hadamard transformed image reconstruction for an equilateral triangle of 1-inch side length with a 3-mm-width metal strip across it. As reference, the outline sketch of the triangle aperture object with a metal strip across is also shown.

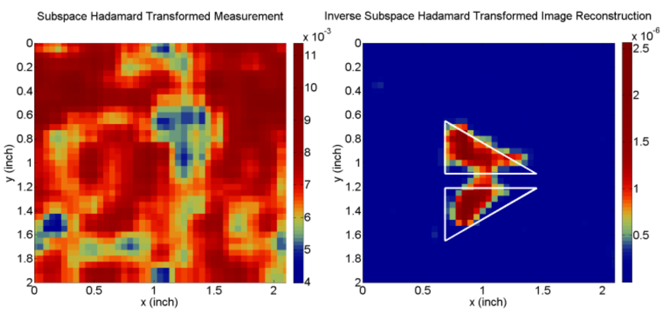

Fig. 4. Left plot: interpolated Hadamard transformed measurement from $1/9$ *of Hadamard space; and right plot: reconstructed image.*

C. Passive Imaging

Figure 5 shows a single-pixel passive millimeter-wave setup for Hadamard transform imaging. An incandescent 60W light bulb is used as an illumination source. For the target to be imaged, we used a 2.54cm diameter circular hole in a 10cm × 10cm metal plate along with a 3mm wide rectangular strip pasted across the hole. An extended Hadamrd mask is raster scanned in front of the scene, and the illuminated radiation through each mask position and scene is collected by a 2.54cm diameter dielectric lens and fed to a 146-154 GHz Dicke-switched radiometer [4].

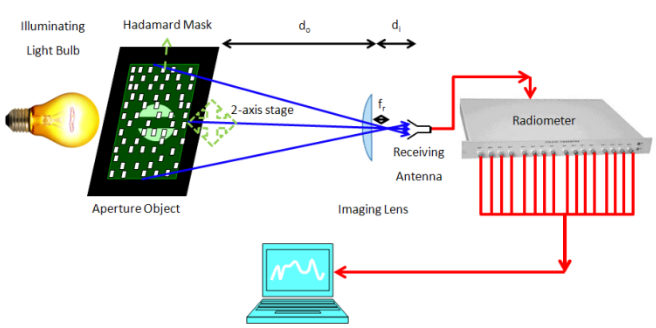

Fig. 5. Schematics showing passive mmW Radiometer using subwavelength Hadamard transform.

Fig. 6 shows the full Hadamard measurement space (5-second integration time) on the left and the corresponding recovered image on the right. Figure 7 gives imaging results of the same scene with 1/9 of the samples, showing the target image with comparable quality as in Fig. 6.

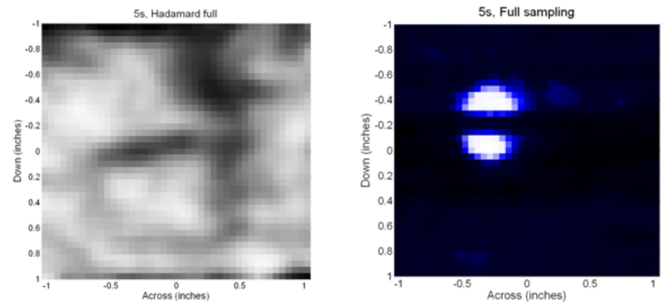

Fig. 6. Left: Hadamard space and right: Reconstructed image for full set of acquisitions.

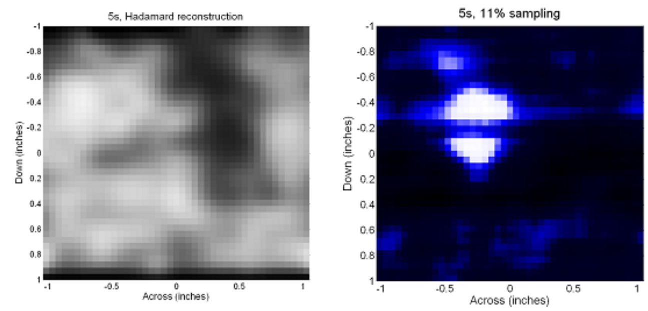

Fig. 7. Left: interpolated Hadamard space using 1/9 of full measurements and right: Reconstructed image.

III. CONCLUSIONS

We have successfully implemented the compressive sampling scheme for both active and passive mmW imaging based on Hadamard transform. The image quality of the active system appears to be slightly inferior to that of the passive mmW system due to coherent scattering by the subwavelength features of the mask in the active system. However, it has been shown that high-fidelity images can be recovered with only $1/9$ of the full Hadamard measurements for both the cases.

ACKNOWLEDGEMENT

The work is supported by the office of Nonproliferation and Verification Research and Development under the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

REFERENCES

[1] M. F. Duarte etc., "Single-pixel imaging via compressive sensing," *IEEE Signal Processing Magazine*, 83-91, 2008.

[2] M. Harwit, and N. Sloane, Hadamard Transform Optics, New York: Academic Press, 1979.

[3] J. D. Jackson, Classical Electrodynamics, New York: Wiley, 1998.

[4] N. Gopalsami, T. Elmer, Shaolin Liao, R. Ahern, A. Heifetz, A. C. Raptis, M. Luessi, D. Babacan and A. K. Katsaggelos, "Compressive sampling in passive millimeter-wave imaging," Proc. SPIE 8022, 80220I, 2011.