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Single-Pixel Chaotic Cavity Bandwidth Control using Rotman Lens-based Multiplexer/Demultiplexer

Ilyas Saleem(1), Muhammad Ali Babar Abbasi(2), Vincent Fusco(2), Okan Yurduseven(2), Syed Muzahir Abbas(1), and Subhas Mukhopadhyay(1)

(1) School of Engineering, Faculty of Science and Engineering, Macquarie University, NSW 2109, Australia
ilyas.saleem@hdr.mq.edu.au, {syed.abbas, subhas.mukhopadhyay}@mq.edu.au
(2) Centre for Wireless Innovation, Institute of Electronics, Communications & IT, Queen's University Belfast, UK
{m.abbasi, v.fusco, okan.yurduseven}@qub.ac.uk

***Abstract*—This paper presents the integration of a microwave multiplexer/demultiplexer based on a Rotman Lens, with a cavity-backed metasurface antenna, for the first time, which represents a key step towards achieving efficient and cost-effective channel characterisation at microwave frequencies. Converting wideband signals into multiple sub-band signals and distributing their computations to parallel processing units can enable high-performance characterisation with low-order computational complexities.**

I. Introduction

5th Generation (5G) and Beyond 5G (B5G) mobile networks are developed to fulfil the insistence of high data rates and improved connectivity. This became a reality due to the availability of wide bandwidths in newly introduced frequency spectra ranging from microwave to millimeter-waves. With the help of medium and smaller wavelengths in these spectra, simultaneous directive analogue beams with high gain are possible, yet these beams still struggle to provide sufficient coverage for multiple users. Similarly, only directive beams are not enough, if the intent is to power up small sensors, B5G, or Internet of Things (IoT) devices using the Simultaneous Wireless Information and Power Transfer (SWIPT) techniques [1]. To cater this dilemma, multi Beamforming surfaces, also referred as coded metasurfaces, emerged as one of the promising and adaptive solutions which effectively increase the coverage and scanning angles while offering flexibility in terms of beam steering or direction pointing granularity [2]. These surfaces are even more promising when they require only a single Radio Frequency (RF) path. The only downside is the enhanced computational complexity when the single wideband signal is to be processed.

II. Proposed Approach

Since wideband signals are more complex and require more computational power for channel characterisation in comparison to narrowband signals, we propose to couple the Rotman lens (RL) - based multiplexer/demultiplexer with a frequency-diverse chaotic cavity to convert the wideband signals into multiple sub-band signals, which can be later computed with low-order computational complexities. By converting the incoming wideband signal into a series of narrowband signals and distributing their computations, separate processing units can be introduced to systematically improve the overall channel characterisation speed while reducing the hardware's capital and operational cost. The system architecture presented in Fig. 1, shows a single RF path which connects the chaotic cavity and the RL operating as multiplexer/demultiplexer. The RL is based on microstrip technology. The output signal of chaotic cavity is fed to the central beam port of RL and all the array ports are connected with an Arrayed Waveguide Grating (AWG). The multiplexed/demultiplexed output from RL is extracted from its remaining beam ports for further parallel processing.

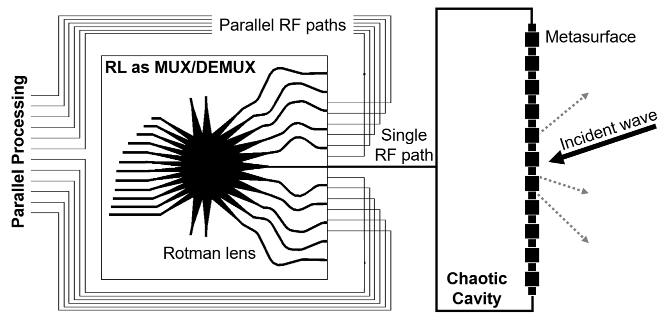

Fig. 1: Frequency-diverse chaotic cavity connected to a Rotman Lens-based multiplexer/demultiplexer, enabling parallel processing to reduce computational complexity.

III. Operation, Results and Discussion

The RL-based multiplexer/demultiplexer is comprised of RL and a transmission line-based AWG region [3]. The RL structure used in this investigation, shown in Fig. 2(a), is same as presented in [4]. The different electrical path lengths between an input and output port trigger time delays in signal transmission. Thus, being a True-Time-Delay (TTD) device, RL generates frequency independent linearly evolved phase shift beams without using an active and complex phase control [5]. Therefore, RL is preferred over phase shifters or switches for beam scanning and beam steering [6]. In [3], transmission line-based AWG region is combined with RL to be used as a microwave multiplexer/demultiplexer. Multiple phase shifters of identical phase differences constitute this AWG region. The RL is performing two operations: first it equally divides the multispectrum input signal to every array port and in the second place, it returns a discrete frequency signal to different beam ports. By changing grating order, any frequency can be multiplexed or demultiplexed on a desired beam port.

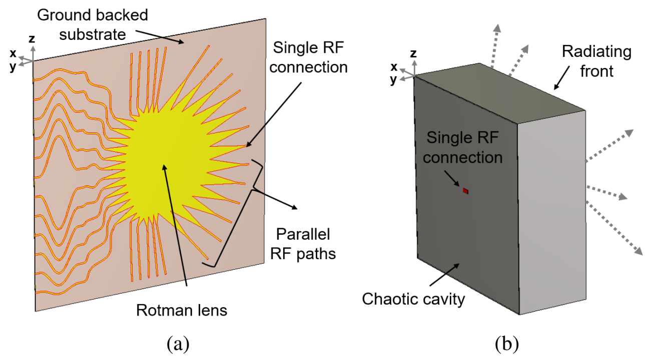

Fig. 2: (a) RL used to develop the multiplexer/demultiplexer. (b) Frequency diverse chaotic cavity with radiating aperture.

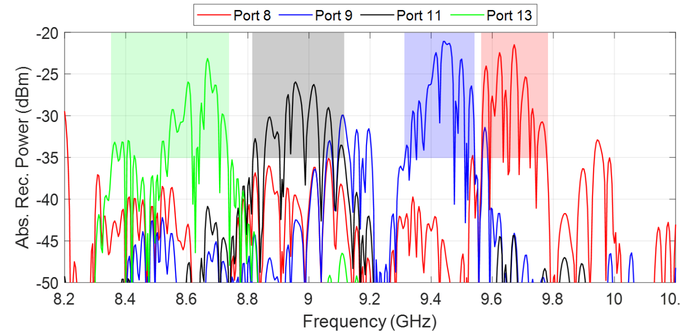

Fig. 3: Absolute received power at multiple beam ports indicating sub-bands for parallel processing.

The chaotic cavity exhibited in Fig. 2(b) is similar to the one in presented in [2], [7]. In [7], a comprehensive explanation of chaotic cavity's operational mechanism is also offered. The chaotic cavity is aligned to operate as a frequency-diverse metasurface. This formation recommends utilising a single RF chain equipment as the source information signal is compressed in a single channel when the chaotic cavity is acting as a compressive medium. Such configuration is used to estimate the Direction of Arrival (DoA) of the impinging signal in [7].

Similarly, in [8], the diversity limitations of the frequency-diversity antenna mechanism, employed for a different yet related applications of microwave imaging are reduced by managing and controlling the cavity modes. The cavity front (metasurface) radiates distinctively at each frequency resulting in unique radiation patterns. Once known to the computational layer how the radiation pattern will look for every frequency and how many frequency modes will be there, a parallel processing unit can use computational approaches to proficiently perform the channel characterisation.

The results shown in Fig. 3 verify the viability of the proposed approach. Here, the signals received at multiple array ports are plotted, and the split of a single wideband signal into sub-bands is clearly observable. Each port, connected to its own computational processor can enable the required parallel processing in a much narrower bandwidth. This can reduce the computational complexity by a factor of $N_b - 1$ times, where N_b is the number of beam ports of the RL operating as multiplexer/demultiplexer. It should be noted, however, that when the operating frequency band is partitioned into narrower sub-bands, each channel is allocated fewer measurements. This can reduce the quality of the estimation obtained from each channel, resulting in reduced fidelity of the final channel image. Therefore, it may be necessary to stitch information acquired across the sub-bands together post parallel processing in a digital signal processing domain to facilitate channel characterization. To address this challenge, a linear algorithm e.g. matched-filtering can be used to process each channel's data and combine the reconstructions to obtain a more meaningful result. This will be further investigated in the follow-up studies.

By learning the frequency-diverse cavity modes and their respective radiation patterns against every frequency, it is anticipated that the presented configuration can provide solid foundations for the development of fast and accurate channel characterisation in B5G wireless networks.

IV. Conclusions

A novel proposition of translating wideband signal into multiple sub-bands and then employing individual processing is introduced. A chaotic cavity-backed metasurface antenna with known radiation characteristics, when used as a receiver, possesses orthogonal radiation modes while the data received against each frequency is processed at a computational layer. By acting as a multiplexer/demultiplexer, RL offers exclusive modes to be divided and delivered at different ports, which can be then linked to multiple parallel computational units, eventually enhancing the channel characterisation.

V. Acknowledgements

This work is partially supported by the UKRI under Project Award 10062167, Leverhulme Trust under Research Leadership Award RL-2019-019, and Department for the Economy under US-Ireland R&D Partnership Programme project 199.

References

[1] K. Niotaki and et. al, "Rf energy harvesting and wireless power transfer for energy autonomous wireless devices and rfids," in *IEEE Journal of Microwaves*, vol. 3, no. 2, April 2023, pp. 763–782.

[2] O. Yurduseven, M. A. B. Abbasi, T. Fromenteze, and V. Fusco, "Compressive sensing as applied to channel characterization and beam synthesis at microwave frequencies," in *3rd URSI Atlantic and Asia Pacific Radio Science Meeting (AT-AP-RASC)*. IEEE, 2022, pp. 1–4.

[3] Y. Zhang and V. Fusco, "Rotman lens used as a demultiplexer/multiplexer," in *European MW Conference*, 2012, pp. 164–167.

[4] S. Christie, R. Cahill, N. B. Buchanan, V. Fusco, N. Mitchell, Y. V. Munro, and G. Maxwell-Cox, "Rotman lens-based retrodirective array," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 3, pp. 1343–1351, 2011.

[5] R. Rotman, M. Tur, and L. Yaron, "True time delay in phased arrays," *Proceedings of the IEEE*, vol. 104, no. 3, pp. 504–518, 2016.

[6] A. Darvazehban, O. Manoochehri, M. A. Salari, P. Dehkhoda, and A. Tavakoli, "Ultra-wideband scanning antenna array with rotman lens," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp. 3435–3442, 2017.

[7] M. Abbasi, V. Fusco, O. Yurduseven, and T. Fromenteze, "Frequency-diverse multimode millimetre-wave constant-ϵ_r lens-loaded cavity," *Scientific Reports*, vol. 10, no. 1 (22145), pp. 1–12, 2020.

[8] T. V. Hoang, T. Fromenteze, M. Abbasi, C. Decroze, M. Khalily, V. Fusco, and O. Yurduseven, "Spatial diversity improvement in frequency-diverse computational imaging with a multi-port antenna," *Results in Physics*, vol. 22, no. 103906, pp. 1–8, 2021.