SPACE-TIME METASURFACE OPTIMISATION AND APPLICATION

INTRODUCTION

Space-time metasurfaces (STM)

- Artificial surface of sub-wavelength scale periodic elements
- EM wave manipulation to control scattering of incoming electromagnetic wave harmonics; wavefront control (steering, focusing) allows for increased gain & decreased parasitic radiation
- Important in many areas of research – photonics, communications, remote sensing, etc.

Primary challenge: generate space-time matrix (STMx) that fulfils specific requirements for various applications

THEORETICAL BACKGROUND

Eliminated time-dependence of time-periodic space-time matrix Γ by Fourier transform

$$\Gamma = \sum_{b=1}^{L} \frac{\Gamma_{pq}^{n}}{\pi m} \sin[\frac{\pi m}{L}] e^{-\frac{i\pi m(2b-1)}{L}}$$

m: harmonic number, (N, M): (x,y) space lengths of STMx, L=time length of STMx, k_1: incident wave wavenumber, k_1: outgoing wavenumber, Γ_{pq}^{n}: reflection coefficient of (p,q) element during interval $(n-1)\tau \le t \le n\tau$

Far-field pattern derived from phasor sum of E-field contributions from each element [1]:

$$E(\theta,\phi) = \sum_{q=0}^{N-1} \sum_{p=0}^{M-1} E_{p,q}(\theta,\phi) \exp\{jk_2(pd_x \sin\theta \cos\phi + qd_y \sin\theta \sin\phi)\}$$

$$\sum_{b=1}^{L} \frac{\Gamma_{pq}^{n}}{\pi m} \sin[\frac{\pi m}{L}] e^{-\frac{j\pi m(2b-1)}{L}}$$

To account for near-field & oblique incidence cases, we simply add a phase shift to the summation:

Near-field: $\exp\left\{jk_1 \left| \vec{r} - \begin{pmatrix} pd_x \\ qd_y \\ 0 \end{pmatrix} \right| \right\}$

Oblique incidence: $\exp\{jk_1(pd_x \sin\theta_i \cos\phi_i + qd_y \sin\theta_i \sin\phi_i)\}$

OPTIMISATION

To improve applicability of STM:

- Deflect main beam of a specific harmonic to desired angle
- Suppress all other harmonics and sidelobes

However, this problem is difficult to solve analytically (due to large x^n space of solution)

Apply Genetic Algorithm ($\mu + \lambda - GA$) (population of μ and recombination pool of λ) [2]

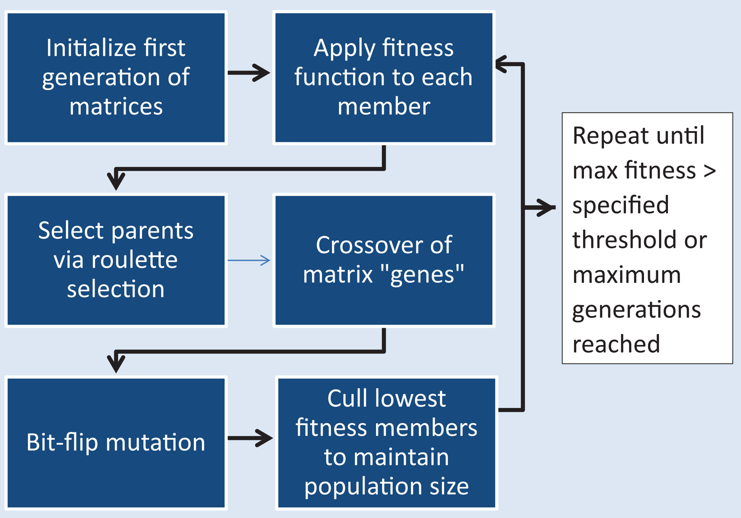
Fitness function defined as $4\sum_i (x_{p_i} - x_{p_i,0}) - \max(p_1, \dots, p_i, i \ne i_{\text{shift}})$

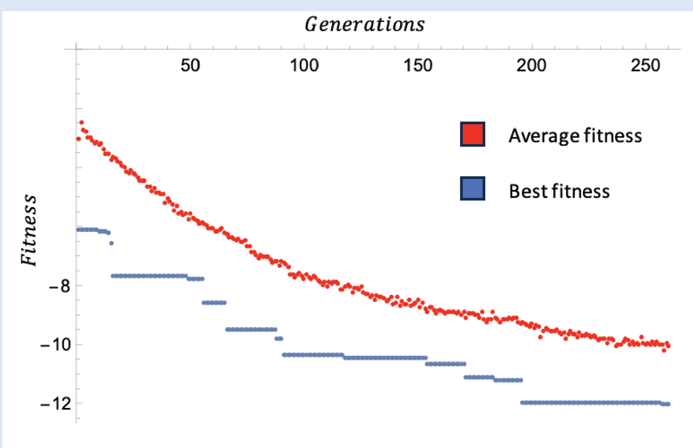
- Weighting constant to emphasize beam steering over sidelobe suppression
- Penalizes increasing main beam distance (x_{p_i}) from steering angle ($x_{p_i,0}$)
- Penalizes large sidelobes or harmonic peaks (p_i)

Hyperparameters:

- Replacement rate = 0.25
- Mutation rate = 0.05
- Crossover probability = 0.9
- Initial population size = 100

Able to reach convergence in about 200 generations, each run takes less than 30 minutes to reach optimum.





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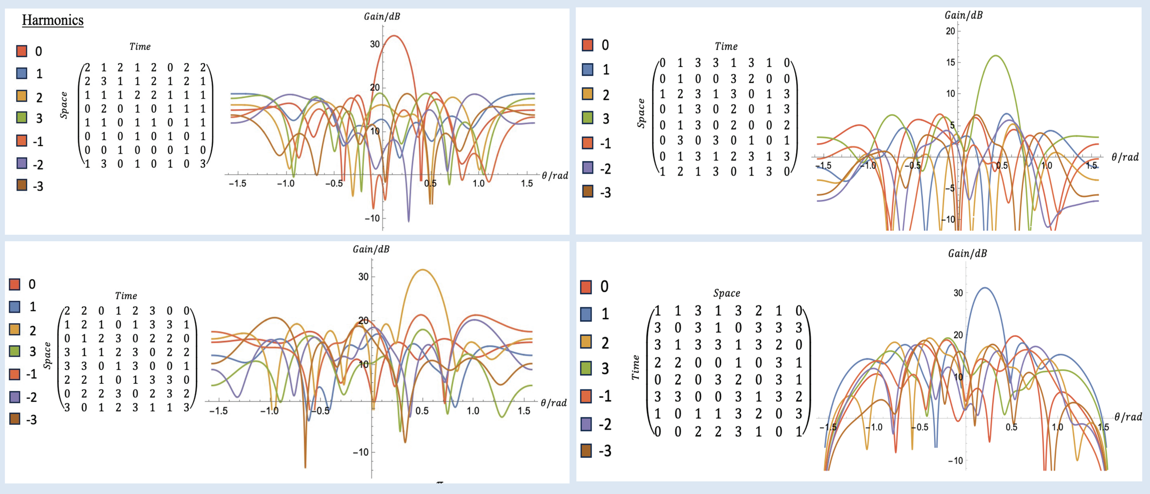
RESULTS & DISCUSSION

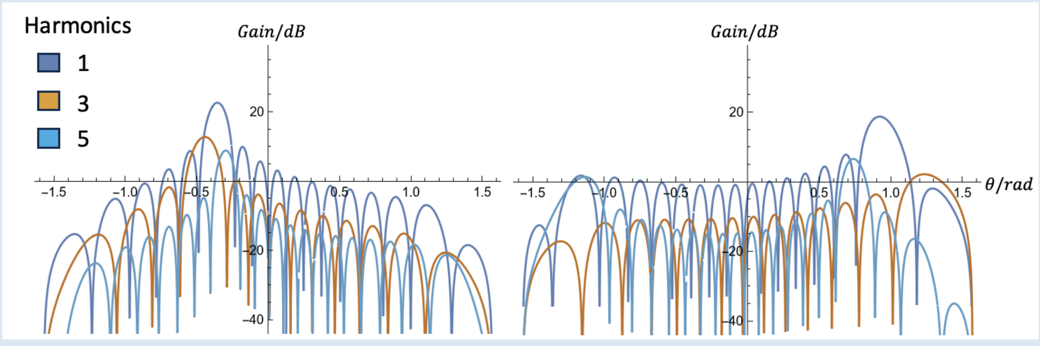
(i) Deflect harmonics in arbitrary directions,

(ii) Minimize sidelobes & other harmonics to a reasonable extent (>10dB below) for normal incidence, oblique incidence, and near-field



(Top-L) Normal plane wave incidence, steer beam of fundamental frequency to 10° (Bottom-L) Normal plane wave incidence, steer beam of 2nd harmonic to 30° (Top-R) Near-field incidence, steer beam of 3rd harmonic to 30° (Bottom-R) Oblique plane wave incidence at 30°, steer beam of 1st harmonic to 15°

Observed non-reciprocity for oblique incidence case



Nonreciprocity of metasurface

(L) f_0 (5 GHz) wave incident at $\theta^i = 60°$, f_1 (1st harmonic @ 5.25 GHz) beam deflects to $\theta^s = -20.3°$

(R) f_0 (@ 5.25 GHz) wave incident at $\theta^i = -20.3°$, 1st harmonic (@ 5.5 GHz) beam deflects to $\theta = +51.2°$

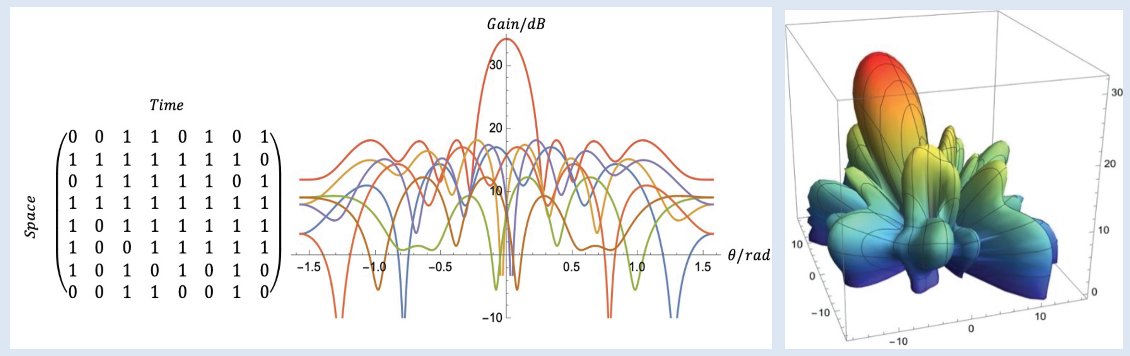
STM Parameters

- Increasing no. of STMx bits speeds up convergence + improves optimization
- Increasing STMx size slows down convergence + improves optimization
- No significant difference between optimization quality for different incidence scenarios

Method can be generalised to related fields

(L) Demo of optimization (sidelobe suppression) for Time-Modulated Linear Array (TMLA)

(R) Demo of optimization (beam steering & sidelobe suppression) for 8x8 element reflectarray antenna



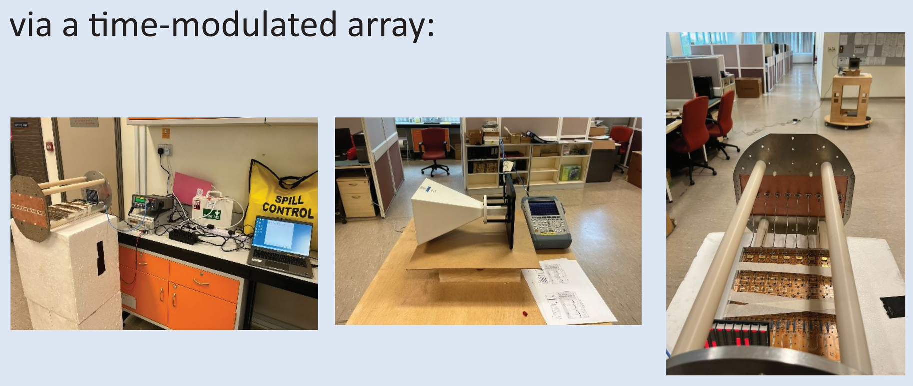
EXPERIMENTAL VERIFICATION

Simulated space-time metasurface via a time-modulated array:

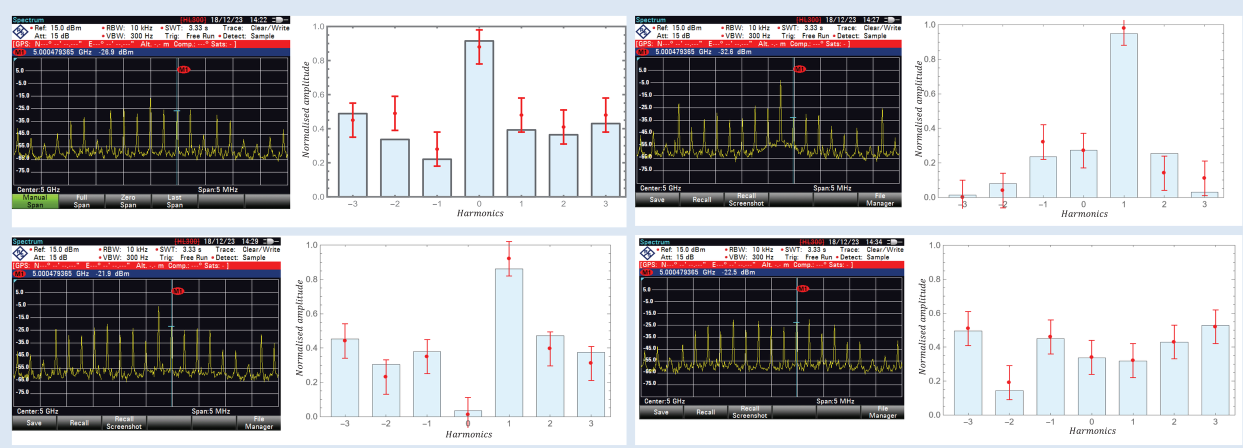
(R) Complete view of setup

(L) STM side with array & its RF backend, power supply & controller

(M) Receive horn connected to spectrum analyser.



(1) **Very good agreement** found between predicted & observed harmonic power distribution (most deviations within experimental error):



(2) Beam steering in the **predicted direction** observed

CONCLUSION AND FUTURE WORK

- Demonstrated capabilities of STM for beam steering and suppression of sidelobes & harmonics in both near-field & far-field incidence cases using genetic optimisation
- Verified theoretical results with experimental data, obtained good fit with theory
- Proved applicability of our method in generating optimised STMx

References

1. Zhang, L., Chen, X.Q., Liu, S. *et al.* Space-time-coding digital metasurfaces. Nat Commun 9, 4334 (2018). https://doi.org/10.1038/s41467-018-06802-0
2. Slowik, A., Kwasnicka, H. Evolutionary algorithms and their applications to engineering problems. Neural Comput & Applic 32, 12363–12379 (2020). https://doi.org/10.1007/s00521-020-04832-8

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YDSP Young Defence Scientists Programme

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