Experimental evaluation of 3D printed spiral phase plates for enabling an orbital angular momentum multiplexed radio system

B. Allen, T. Pelham, Y. Wu, T. Drysdale, D. Isakov, C. Gamlath, C. J. Stevens, G. Hilton, M. A. Beach and P. S. Grant

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Original submission: 6 September 2019
Revised submission: 6 November 2019
Final acceptance: 14 November 2019

Note: Reports are unedited and appear as submitted by the referee. The review history appears in chronological order.

Review History

RSOS-191419.R0 (Original submission)

Review form: Reviewer 1

Is the manuscript scientifically sound in its present form?
Yes

Are the interpretations and conclusions justified by the results?
Yes

Is the language acceptable?
Yes

Do you have any ethical concerns with this paper?
No
Have you any concerns about statistical analyses in this paper?
No

Recommendation?
Accept with minor revision (please list in comments)

Comments to the Author(s)
Some minor comments:
The authors presented the PPS and lens for OAM generation, and implementation and measurement results are provided.  
1. The authors are suggested to correct some grammatically issues in the paper.  
   ‘We suggest a mode multiplexer architecture that is expected to further reduce the crosstalk for each mode is employed.’ Which appeared twice in the paper.

   In summary, ‘seek ways to reduce material’ should be ‘seeking ways …’;
   ‘topological charge’ should be ‘topological change’
   ‘This compares with 13 dB achieved’, should it be -13 dB?

   On page 10, ‘with this lens and this a larger diameter lens or sub …’, please rewrite.

2. The authors use ‘S’ to represent two different parameters in the paper, please change one of them.


Review form: Reviewer 2 (Anas Mohsin)

Is the manuscript scientifically sound in its present form?
Yes

Are the interpretations and conclusions justified by the results?
Yes

Is the language acceptable?
Yes

Do you have any ethical concerns with this paper?
No

Have you any concerns about statistical analyses in this paper?
No

Recommendation?
Accept with minor revision (please list in comments)

Comments to the Author(s)
Use of OAM in the millimetre wave (mmwave) regime is certainly a promising approach to deliver increased spectral efficiency, especially given that both OAM and mmwave require line-of-sight to achieve meaningful gain in system capacity. The paper is very well-written and easy to
follow. I therefore recommend this paper to publications. However, I have minor comments to the authors which can benefit those who are interested in this subject.

1- The authors discussed multiple modes of OAM, how do these modes differ? do they share the same wave number, dispersion and wave-impedance or are they fundamentally different?

2- It is not clear if MIMO precoding can play a role in mitigating the encountered cross-talk. Have the authors considered the use of the eigen-modes of OAM if there're any?

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9- It's clear that the lens improved the channel gain of the diagonal channel coefficients however the impact on the off-diagonal is unclear. The authors may want to rephrase, addressing (7) will resolve this point.

Overall, the paper is definitely worth publishing and the subject is timely, relevant and stimulating.

Decision letter (RSOS-191419.R0)

28-Oct-2019

Dear Dr Allen

On behalf of the Editors, I am pleased to inform you that your Manuscript RSOS-191419 entitled "Experimental Evaluation of 3D Printed Spiral Phase Plates for enabling an Orbital Angular Momentum Multiplexed Radio System" has been accepted for publication in Royal Society Open Science subject to minor revision in accordance with the referee suggestions. Please find the referees' comments at the end of this email.

The reviewers and handling editors have recommended publication, but also suggest some minor revisions to your manuscript. Therefore, I invite you to respond to the comments and revise your manuscript.
• Ethics statement
If your study uses humans or animals please include details of the ethical approval received, including the name of the committee that granted approval. For human studies please also detail whether informed consent was obtained. For field studies on animals please include details of all permissions, licences and/or approvals granted to carry out the fieldwork.

• Data accessibility
It is a condition of publication that all supporting data are made available either as supplementary information or preferably in a suitable permanent repository. The data accessibility section should state where the article's supporting data can be accessed. This section should also include details, where possible of where to access other relevant research materials such as statistical tools, protocols, software etc can be accessed. If the data has been deposited in an external repository this section should list the database, accession number and link to the DOI for all data from the article that has been made publicly available. Data sets that have been deposited in an external repository and have a DOI should also be appropriately cited in the manuscript and included in the reference list.

If you wish to submit your supporting data or code to Dryad (http://datadryad.org/), or modify your current submission to dryad, please use the following link:
http://datadryad.org/submit?journalID=RSOS&manu=RSOS-191419

• Competing interests
Please declare any financial or non-financial competing interests, or state that you have no competing interests.

• Authors’ contributions
All submissions, other than those with a single author, must include an Authors’ Contributions section which individually lists the specific contribution of each author. The list of Authors should meet all of the following criteria; 1) substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; 2) drafting the article or revising it critically for important intellectual content; and 3) final approval of the version to be published.

All contributors who do not meet all of these criteria should be included in the acknowledgements.

We suggest the following format:
AB carried out the molecular lab work, participated in data analysis, carried out sequence alignments, participated in the design of the study and drafted the manuscript; CD carried out the statistical analyses; EF collected field data; GH conceived of the study, designed the study, coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

• Acknowledgements
Please acknowledge anyone who contributed to the study but did not meet the authorship criteria.

• Funding statement
Please list the source of funding for each author.

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the end statements for reference. If you feel that a given heading is not relevant to your paper, please nevertheless include the heading and explicitly state that it is not relevant to your work.

Because the schedule for publication is very tight, it is a condition of publication that you submit the revised version of your manuscript before 06-Nov-2019. Please note that the revision deadline will expire at 00.00am on this date. If you do not think you will be able to meet this date please let me know immediately.

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When submitting your revised manuscript, you will be able to respond to the comments made by the referees and upload a file "Response to Referees" in "Section 6 - File Upload". You can use this to document any changes you make to the original manuscript. In order to expedite the processing of the revised manuscript, please be as specific as possible in your response to the referees. We strongly recommend uploading two versions of your revised manuscript:

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2) A 'clean' version of the new manuscript that incorporates the changes made, but does not highlight them.

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Supplementary files will be published alongside the paper on the journal website and posted on the online figshare repository (https://rs.figshare.com/). The heading and legend provided for each supplementary file during the submission process will be used to create the figshare page, so please ensure these are accurate and informative so that your files can be found in searches. Files on figshare will be made available approximately one week before the accompanying article so that the supplementary material can be attributed a unique DOI.

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Once again, thank you for submitting your manuscript to Royal Society Open Science and I look forward to receiving your revision. If you have any questions at all, please do not hesitate to get in touch.

Kind regards,
Anita Kristiansen
Editorial Coordinator
Royal Society Open Science
openscience@royalsociety.org

on behalf of Professor Weisi Guo (Associate Editor) and R. Kerry Rowe (Subject Editor)
openscience@royalsociety.org

Reviewer comments to Author:
Reviewer: 1

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Some minor comments:
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1. The authors are suggested to correct some grammatically issues in the paper.
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Reviewer: 2

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9- It's clear that the lens improved the channel gain of the diagonal channel coefficients however the impact on the off-diagonal is unclear. The authors may want to rephrase, addressing (7) will resolve this point.

Overall, the paper is definitely worth publishing and the subject is timely, relevant and stimulating.

Author's Response to Decision Letter for (RSOS-191419.R0)

See Appendix A.

Decision letter (RSOS-191419.R1)

14-Nov-2019

Dear Dr Allen,

It is a pleasure to accept your manuscript entitled "Experimental Evaluation of 3D Printed Spiral Phase Plates for enabling an Orbital Angular Momentum Multiplexed Radio System" in its
current form for publication in Royal Society Open Science. The comments of the reviewer(s) who reviewed your manuscript are included at the foot of this letter.

Please ensure that you send to the editorial office an editable version of your accepted manuscript, and individual files for each figure and table included in your manuscript. You can send these in a zip folder if more convenient. Failure to provide these files may delay the processing of your proof. You may disregard this request if you have already provided these files to the editorial office.

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Thank you for your fine contribution. On behalf of the Editors of Royal Society Open Science, we look forward to your continued contributions to the Journal.

Kind regards,
Andrew Dunn
Royal Society Open Science Editorial Office
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openscience@royalsociety.org

on behalf of Professor Weisi Guo (Associate Editor) and R. Kerry Rowe (Subject Editor)
openscience@royalsociety.org

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Appendix A

Dear Royal Society Open Science editor and reviewers,

We would like to thank you for considering our paper and for the positive response. On behalf of all authors, I have worked through the comments and made changes to the paper where appropriate. I enclose the updated paper with changes highlighted as well as a ‘clean’ version. A response to each of the comments is given below.

I hope you find this response sufficient to warrant publication.

Kind regards,

Ben Allen and co-authors

Reviewer comments to Author:

Reviewer: 1

The authors presented the PPS and lens for OAM generation, and implementation and measurement results are provided.

1. The authors are suggested to correct some grammatically issues in the paper.
   ‘We suggest a mode multiplexer architecture that is expected to further reduce the crosstalk for each mode is employed.’ Which appeared twice in the paper. Good spot. Change made.

   In summary, ‘seek ways to reduce material’ should be ‘seeking ways ...’; Good spot. Change made.

   ‘topological charge’ should be ‘topological change’

   The term ‘topological charge’ is considered to be correct in the context of this paper. The term refers to an integer that describes the mode number. It stems from quantum physics, ‘topological quantum charge’. In the case of OAM modes, it refers to the number of phase ‘twists’ the beam exhibits in a single wavelength, thus the angular phase velocity.

   ‘This compares with 13 dB achieved’, should it be -13 dB? Good spot and correction made.

On page 10, ‘with this lens and this a larger diameter lens or sub ...’, please rewrite. Done.

2. The authors use ‘S’ to represent two different parameters in the paper, please change one of them. Good spot. The first usage of s has now been changed to \( \chi \).

Thank you very much for taking time to review our manuscript. We hope you find our response sufficient to recommend publication.

Reviewer: 2

Use of OAM in the millimetre wave (mmwave) regime is certainly a promising approach to deliver increased spectral efficiency, especially given that both OAM and mmwave require line-of-sight to
achieve meaningful gain in system capacity. The paper is very well-written and easy to follow. I therefore recommend this paper to publications. Thank you very much.

However, I have minor comments to the authors which can benefit those who are interested in this subject.

1- The authors discussed multiple modes of OAM, how do these modes differ? do they share the same wave number, dispersion and wave-impedance or are they fundamentally different?

   The modes differ in three ways, as follows.

   i. As the mode order increases, the width of the vortex increases. In other words, the diameter of the ‘doughnut’ shape in the amplitude radiation pattern increases.

   ii. As the mode order increases, the number of phase ‘twists’ around the centre of the phase radiation pattern increases.

   iii. Modes can be negative or positive, which refers to the ‘handedness’ of the phase twist mentioned above.

   OAM modes actually refer to a class of modes called Laguerre Gaussian modes (LG modes), which can be created from a combination of standard waveguide modes.

2- It is not clear if MIMO precoding can play a role in mitigating the encountered cross-talk. Have the authors considered the use of the eigen-modes of OAM if there’re any?

   MIMO processing does play a role. It can be used to reduce interference caused by modal crosstalk. However the focus of the work does in the paper is the antenna engineering to create OAM modes that are as clean as possible. MIMO processing can be used to mop up any residue interference.

   One way of analysing OAM modes is by standard MIMO analysis, and thus by considering the eigenmodes that are generated. This method is suited for the case when OAM modes are generated / received by circular antenna arrays. This is not the approach taken in this work, but has been considered by others.

   MIMO Waterfilling also has a place in optimally allocating resources across modes.

3- Given that OAMs are non-plane waves, is there a scope for use of reflective materials without comprising the orthogonality of OAMs in non-line of sight channels? Yes there is. In fact, this is the approach taken by early OAM radio work. The experiment took place in Venice circa 2010 and used a parabolic dish that was split across the radius to create an OAM mode.

4- On the crosstalk levels, would the use of spatial filters (digital eg using the null-space) help in reducing crosstalk, this is related to comment no 2

   Please see response to your comment 2.

5- Page 4, first line, it's grammatically more accurate to use "that" in "means it is important..." Good spot and correction made.
6- In Page 3, lines 39-42, spaces are required between the number and the start of the lines. Good spot and correction made.

7- The authors are recommended to include a channel scattering matrix to demonstrate the individual coupling coefficients for a sample frequency with and without lens to improve readability.

Please see tables 1-4 at the end of the manuscript. These are tables giving the crosstalk levels between modes for a range of circumstances. Whilst these aren’t the channel scattering matrices, they do indicate similar information as that derived from the scattering matrix. We do not have these measurements and it would be tricky to obtain them. However it is a good suggestion that we should take on board for future work.

8- Equation (4) seems fundamental to the orthogonality of OAMs, although the authors discuss angular fourier transform, it’s not entirely clear equation (5) dictates equation (4), would be useful to clarify this. As a reader, I expect the optimal solution for equation (4) is fourier-based.

Equation 4 describes the phase pattern for a particular OAM mode. On the other hand, equation 5 is an analytical tool that enables the mode spectrum for a particular phase pattern to be determined. Of course, an ideal set-up would have a single mode that results in a single line on the angular Fourier transform. This can also be spotted by examining (4). However in a realistic system (4) will not hold and the resultant is a summation of several modes (Fourier series). This unknown composite mixture of modes can be determined from (5). I hope this claries somewhat.

9- It’s clear that the lens improved the channel gain of the diagonal channel coefficients however the impact on the off-diagonal is unclear. The authors may want to rephrase, addressing (7) will resolve this point.

Thank you for this comment. Please see our response to (7), which we hope addresses this point too. Please note that we haven’t taken the scattering matrix approach in this work but it is a good suggestion to take forward for future work.

Overall, the paper is definitely worth publishing and the subject is timely, relevant and stimulating.

Thank you very much for this positive comment. We hope you find our response to your comments sufficient to recommend publication.