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OPTICAL BEAMFORMING BASED ON MICROWAVE PHOTONIC SIGNAL PROCESSING

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I. INTRODUCTION

Over the past few years considerable attention has been focussed on the inclusion of flexibility in communication satellite payloads. The purpose of this flexibility is to enable a given satellite on command to support different frequency plans, re-configure coverage in response to changing traffic demands and re-configure interconnectivity between coverages. In general flexibility would enable a satellite system to adapt to changing circumstances over its lifetime and thereby maximise its utility and profitability.

A most attractive component in support of flexibility would be a re-configurable antenna system, which would enable the satellite to change its coverage to follow changes in traffic distribution or respond to new, developing market demands. The most flexible of such antenna systems are based on Array Fed Reflector (AFR) or Direct Radiating Array (DRA) architectures. These may use hundreds or thousands of feed elements with interconnectivity provided by a complex beamforming network. Beamforming may be provided either digitally, as in the case of Inmarsat 4 series of satellites, or using analogue means, for example the Boeing Spaceway.

One limitation with digital beamforming is related to the mass and power requirements of the digital processor, which can grow quickly with number of control points, proportional to the number of feed elements and bandwidth per feed. Analogue versions of the beamforming network (BFN) can be constructed. Concern with this type of beamforming is the insertion loss, which increases with numbers of antenna elements (number of signal path divisions), and number of beams, resulting in the need to incorporate embedded amplifiers within the BFN to maintain signal powers at a useable level. An alternative solution may be the use of optical beamforming techniques. These incorporate RF/optical and optical/RF converters at the beamformer interfaces with the beamforming carried out using optical technology. This technology can be embodied in integrated circuits (optical chips) resulting in beamformers of small size, low weight, low insertion loss and with potentially low production and installation costs. Indeed, because the beamforming is carried out optically, save for the RF/optical converters and dimensioning of elements internal to the optical chips, the same design and technology can be used for the optical BFN for the full range of RF applications from L-band up to Ka-band and higher frequencies. Moreover, individual chips can be considered as building blocks, with the BFN of the required scale and functionality built up from these blocks. Such an approach could be a means of providing beam forming networks of large scale and complexity at low cost and with practical features such as low mass, power requirements and insertion loss.

This paper describes an optical beamforming network capable of seamlessly controlling the reception angles of 36 independent beams in a Ku-band receive configuration, employing a phased array receive antenna with 144 antenna elements. The OBFN is fully integrated via a hybrid coupling of two integrated optics platforms.

II. DEFINITION OF MISSION REQUIREMENTS:

Multiple beam missions are frequently the subject of interest from satellite operators, primarily because they offer the potential for high traffic capacity by re-using a limited frequency bandwidth [1]. Historically the solution has been reflector based, either with Single Feed Per Beam (SFPB) or AFR with only limited beamforming. These technologies have been selected as the result of a trade-off between mission objectives and the maturity of the technology available.

Satellite based optical beamforming has applications in a wide range of missions, not only in telecommunications satellites but in Earth observation and science. It may be the case that applications outside of telecommunications stimulate the investment needed to develop this technology, and that this will lead to the practical realisation of optically beamformed telecommunications payloads.

The following factors have been taken into consideration in determining the mission requirements:

- Increasing demand for capacity is creating requirements for greater frequency re-use at Ku-band and rapid expansion into the Ka-band. At Ku-band there is an increasing need for beam to beam isolation, for spot beam services and for regional (or linguistic) beams. At Ka-band there has been a proliferation of satellites supporting high data rate services.

- The emerging market in Ka-band high capacity systems is dominated by large aperture reflectors and high numbers of narrow beams. In order to replicate such missions with phased array antennas would require very large apertures, beyond those which could feasibly be accommodated on commercial spacecraft. The number of elements would also be very high.
- Typical antenna configurations for Ka-band high capacity systems use multiple reflector antennas. For a reflector with a single feed per beam the low cross-over levels between adjacent beams would be too low to provide service, so contiguous coverage is provided by interleaving beams from a set of three or four reflectors. An alternative approach would be to generate the beams with subarrays of elements that overlap, a technique that is well suited to low power beamforming such as optical.

For Ku-band applications the level of complexity proposed for the optical beamformer is 144 elements connected to 36 beams. This is consistent with typical commercial missions.

For Ka-band applications there may be an opportunity in the future to implement some of the high capacity multiple beam missions with reflector antennas fed by an array of overlapping subarrays. A typical mission could comprise 100 beams in which no more than 12 elements are connected to any one beam.

A. Antenna Subsystem Definition

The antenna is a Direct Radiating Array (or phased array) design as outlined in Fig. 1.

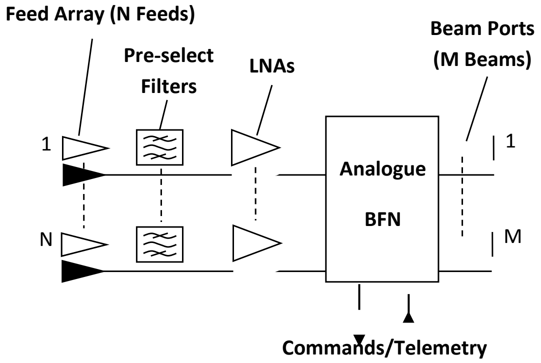

Fig. 1. Receive Antenna Sub-system Summary Block Diagram

The antenna sub-system includes the following features:

- An array of 144 feeds.
- A low loss pre-select filter at the output of each feed or sub-array. The purpose of this is to reject out-of-band signals including image frequencies that may otherwise cause unwanted spurious signals, to protect the active elements from high level leakage from the payload Transmit (Tx) sections and to ensure payload ring-around stability performance.
- A Low Noise Amplifier (LNA) following each pre-select filter.
- An optical beam forming network (OBFN). This is re-configurable and able to support the required number of beams with the coverages defined in the following subsection.
- The general operating frequency band for the antenna sub-system is from 12.75 – 14.50GHz.
- The antenna sub-system operates with linear polarisation in both vertical and horizontal polarisations.

Comments on the above configuration are as follows:

- The gain of the LNA must be sufficient to ensure that the insertion loss of the OBFN has no significant impact on the system noise and hence Gain/System Noise Temperature (G/T) performance.
- In order to reduce the pre-select filter insertion loss and size, the filter is split into two sections with the first section providing necessary protection of the LNA from Tx leakage and the remaining section supporting the other rejection requirements.
- The output ports of the antenna sub-system are beam ports, with each port corresponding to one beam.

B. Antenna Coverage Plots and Polygons

Examples of mission requirements have been reported in above sections and from these, suitable candidates for further investigation have been selected. The primary mission comprises a DRA antenna with 144 radiating elements and up to 36 beams. The sizing of this antenna is sufficient to envelope a number of Ku-band spot beam missions. In addition, a reconfigurable DRA of this complexity can address other requirements such as those detailed below:

- Provision of single zoomable circular and elliptical beams that can be steered over the visible earth surface. Typical requirements are summarised in Table 1 and Table 2.
- Provision of single wide cover beams with arbitrary shape which can be varied on command – for example coverage of the Continental US (CONUS), Europe and India as shown in Fig 2.
- Provision of a small set of irregularly shaped beams, eg “linguistic” beams as shown in Fig 3.
- Provision of larger numbers of spot beams - eg ~70 spots with 1.2° spacing over the Far East as shown in Fig 4 (left).

In addition to the above requirements, a further class of mission was identified for further evaluation. Commercial operators and ESA studies have consistently foreseen applications for large numbers of narrow Ka-band beams, with diameters as low as 0.2 degrees. The large apertures required for such a system make the accommodation of either phased arrays or SFPB multiple reflectors challenging, in which case an AFR antenna offers significant advantages. The requirements for a secondary mission for such a system are provided below and in Fig 4 (right).

- Provision of large numbers of spot beams (100, 200 and more) – eg 200 x 0.2° spot beams over Europe. This layout was provided for the Terabit/s satellite study at Ka-band [2] – [4]. However with regard to the OBFN, the complexity of the architecture will be the same whether Ka-band or Ku-band.

Table 1. Requirements for Single Circular Beam

Requirement	Value	Comments
Min spot beam diameter	1.5°	Spot size zoomable over this range
Max spot beam diameter	5.0°	
Re-pointing range	Full visible earth	

Table 2. Requirements for Individual Elliptical Beam

Requirement	Value	Comments
Min minor axis	1.5°	
Max major axis	5.0°	
Ellipse orientation	± 90°	Variable orientation
Re-pointing range	Full visible earth	

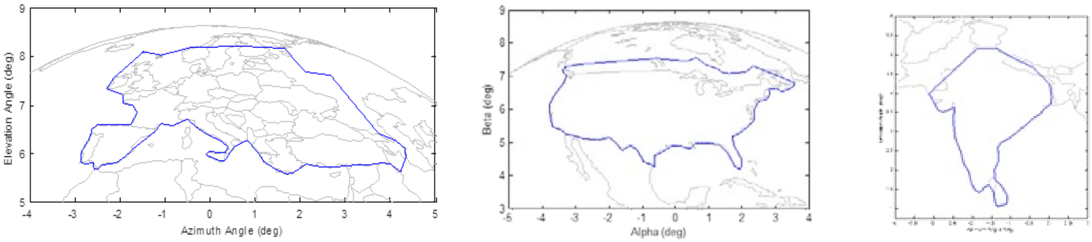

Fig. 2. (left) Wide beam Europe Coverage from Orbital Slot 13°E, (middle) CONUS Coverage from Orbital Slot 267°E, (right) India Coverage Area from Orbital Slot 88°E

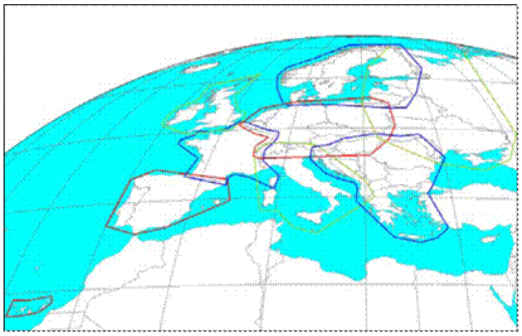

Fig. 3. Provision of 9 Irregularly Shaped “Linguistic” Beams over Europe

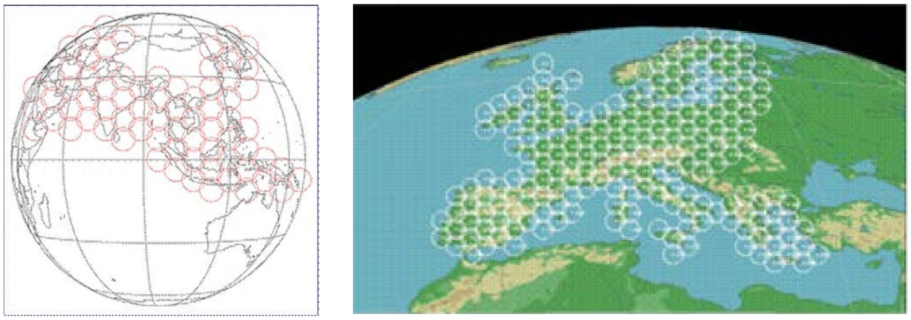

Fig. 4. (left) Coverage of Far East with ~70 Beams with 1.2° Spacing, (right) Coverage of Europe with 200 x 0.2° Beams

III. OBFN FUNCTIONAL DESIGN:

The following 9 options shown in Table 3 were considered for the optical beamformer. These can be categorised in two main types:

1) Each beam is controlled by an individual OBFN. The OBFNs are connected to each other by a complex system of waveguide crossings, multiplexers and de-multiplexers.
2) A single OBFN matrix-type system, capable of addressing all beams.

Table 3. Optical Beamformer Options Considered

option	Short description
1.1	Single laser, many crossings, 36 OBFNs
1.2	144 lasers with different wavelengths, complex MUX/DMUX, 36 OBFNs
1.3	36 lasers with different wavelengths, complex MUX/DMUX, 36 OBFNs
1.4	Single laser split towards 36 OBFNs, each OBFN is connected directly to the antenna array
2.1	Butler Matrix, multi-wavelength
2.2	Blass Matrix, multi-wavelength
2.3	Nolen Matrix, multi-wavelength
2.4	Blass/Nolen Matrix, single wavelength, carrier suppressed, carrier combined with ORR
2.5	Blass/Nolen Matrix, single wavelength, carrier suppressed, carrier combined through matrix

The above nine options for optical beamforming network, are all capable of detecting signals from 36 independent beam directions using an antenna array of 144 antenna elements. For all options, redundancy is roughly equally challenging. In Table 4, a visual overview of the characteristics is given of all nine options.

Table 4. Visual Overview of the Different OBFN Options

Low	Medium	High	Very high
◔	◑	◕	●

Option	Power consumption	Complexity OBFN	Complexity pre-OBFN waveguides	Required number of lasers	Footprint (size)
1.1	●	◔	◑	◔	◕
1.2	●	◔	◕	◕	●
1.3	●	◔	●	◑	●
1.4	●	◔	◔	◑	◕
2.1	?	◑	◔	●	◑
2.2	◕	◑	◔	◕	◑
2.3	◕	◑	◔	◕	◑
2.4	◕	◑	◔	◔	◑
2.5	◕	◕	◔	◔	◑

Based on the overall power consumption, complexity, size and required number of components (i.e., lasers, modulators, detectors) options 1.4 and 2.4 were found to be the best option for further physical layout and design. Option 1.4 consists of a set of 36 binary-tree shaped 144x1 OBFNs using true-time delay (TTD), (i.e. 36 pieces of 144x1 OBFNs), each attached to the full array of antennas (and LNAs). Option 2.4 consists of a

36x144 Nolen matrix. For the remainder of this paper, we will only consider option 1.4 for additional explanation.

A. Comparison of Different OBFN Technologies

A summary comparison of key issues for different OBFN technologies is provided in Table 5.

Table 5. Summary Comparison of Key Issues for Different OBFN Technologies

Parameter	Free-space optics	Fiber-optics	Integrated -optics	Comments
Size	---	-	+++	(- = large, + = small)
Mass	---	+	+++	(- = heavy, + = light)
Cost	--	+	+	(- = expensive, + = cheap)
Vibration sensitivity	--	-	+++	(- = more sensitive, + = less sensitive)
Tunability	++	++	+++	(- = not tunable, + = tunable)
Increasing functionality after fabrication	+++	+	---	(- = not extendible, + = extendible)

The need for using integrated optics rather than free-space optics or fibre-optics arises from the issues associated with thermal and acoustic instabilities and large sized setups in free-space optics and long (and thereby bulky) fibres and expensive Multiplexer/De-multiplexer (MUX/DMUX) devices. If all components can be combined in integrated optical devices, this will reduce thermal and acoustic sensitivity as well as size. As Integrated Optics Optical Beamforming Networks (IO-OBFN) can be fabricated in Complementary Metal–Oxide–Semiconductor (CMOS) factories, the cost of an OBFN in integrated optics can be fairly low when a large number of OBFNs are produced.

B. Waveguide Technologies Overview

As a comparison between the investigated technologies, an overview summary of various waveguide technologies that can be used in an OBFN is presented in Table 6. This overview also includes some of the "exotic" waveguide platforms such as Gallium Arsenide (GaAs) and Lithium Niobate ($LiNbO_3$).

Table 6. Summary Comparison of Waveguide Technologies

Core material	Silica on glass	SiON	Silicon on Insulator	SiO_2/Si_3N_4 TriPleX	GaAs and InP	Lithium Niobate	Comments
RI Contrast (%)	<1	<5	>100	>25	~10	~5	Higher is better
Bending radius (mm)	10-20	0.2-0.8	0.02	0.05	0.1	0.2	Lower is better
Attenuation (dB/cm)	<0.05	0.05-0.3	<2	0.01	2.5	0.2	Lower is better
Transparency	VIS-NIR	VIS-NIR	NIR	VIS-IR	NIR	NIR	Depends on application
Fiber-chip coupling	+++	+	-	+++	--	+	+= better coupling, - = worse coupling
Function integration	-	+	++	+++	++++	+++	+ = many functions on chip, - = less functions
Fabrication cost	++	++	++	+++	--	--	+ = cheap, - = expensive

Recently, many functionalities, like beamforming [5] – [11] and microwave photonic filters have been demonstrated in the SiO_2/Si_3N_4 (TriPleX^{TM}) waveguide technology platform. This waveguide technology is based on a combination of silicon nitride (Si_3N_4) as waveguide layer(s), filled with, and encapsulated by silica (SiO_2). TriPleX^{TM} allows for extremely low loss integrated optical waveguides both on silicon and glass substrates for all wavelengths between 405 nm (near UV) up to 2.35 μm, providing maximum flexibility from an integration standpoint.

It is clear that, although Silicon-on-Insulator (SOI) and Indium Phosphide (InP) have a much higher index contrast and higher refractive (group) index, compared to TriPleX^{TM}, both InP and SOI have too high propagation losses to be feasible as a large-scale IO-OBFN.

For an OBFN the most suitable waveguide technology has a high refractive index (RI) contrast in order to enable to produce small bending radius which is required for making the OBFN devices small enough to fit on a single production wafer. Multiple wafers will cause much higher losses at interconnects between the wafers. The attenuation (waveguide propagation loss) should be as low as possible to be able to have sufficient measureable optical high link gain and low noise figure at the end of the OBFN. Transparency should be sufficient for the chosen wavelength. The mentioned technologies are all transparent for 1550nm wavelength. The fiber-chip coupling should be high; in order to decrease loss at interconnects between fibers and waveguides. Functional integration has to be high to be able to integrate as much as possible on a single wafer.

C. Integrated-optics OBFN

A schematic of a 16x1 OBFN, in receive architecture is shown in Fig 5 (left). It shows a binary tree structure where each circle represents a so-called Optical Ring Resonator (ORR). These ORRs can be used as true-time delay (TTD) devices, because light can travel one or multiple roundtrips through the ORR, depending on the settings of the device. Using these type of resonators, the footprint of the OBFN can be much smaller than when using free-space or fibre-optics. This particular OBFN was fabricated in silicon nitride waveguide material and has 16 inputs and 1 RF output. In current IO-OBFN techniques, the beamformer is fully integrated; however in current state-of-the-art some components are still fibre-coupled or fibre-based.

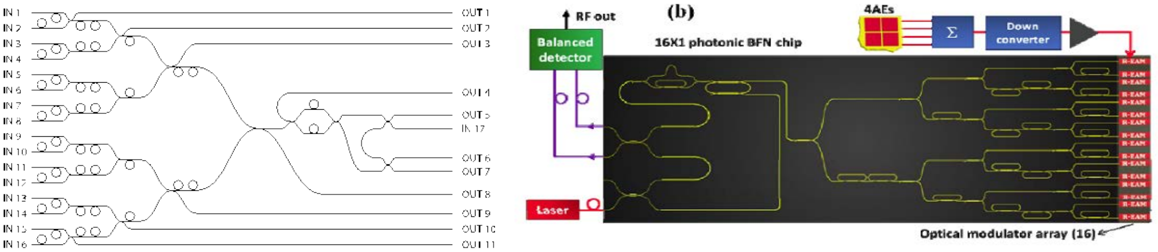

Fig. 5. (left) Schematic of a 16x1 IO-OBFN, (right) Layout with Antennas, Lasers, Modulators and Detectors

The OBFN in Fig 5 (left) is connected to a laser, optical modulators, antennas and detectors as shown in Fig 6 (right). It should be noted that the modulators are reflecting modulators, so the light originating from the laser travels through the OBFN twice.

Current state-of-the-art IO-OBFNs make use of the following critical components:

- **Gain**: fibre-coupled or integrated in different Integrated Optic (IO) platform.
- **Modulator**: fibre-coupled or integrated in different Integrated Optic (IO) platform.
- **Delay line**: usually optical ring resonators (or other types of resonant structures) or switched delay.
- **Detector**: fibre-coupled or integrated in different Integrated Optic (IO) platform.

For a fully functional OBFN, which is also fully integrated, a solution can be found in the combination of active and passive waveguides. Waveguides in active materials should contain parts that can be modulated with high speed (many tens of GHz), can detect light with similar high speeds and *also* can generate (laser) light, all on the same, single chip. However, typically active materials exhibit very high propagation loss. Therefore, a suitable low-loss passive waveguide material has to be applied for the delay-paths of the OBFN.

Currently work is ongoing on combining InP (active) and TriPleX (passive) waveguides in a single package. An example is shown in Fig 7. This example shows InP waveguides incorporating (laser) gain, modulator and multiple detectors. The TriPleX part is low-loss silicon nitride waveguide technology, which can incorporate a laser-mirror to narrow the laser line-width and the delay lines for the OBFN.

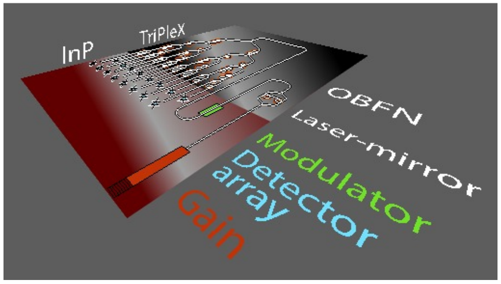

Fig. 7. Combined Active and Passive Waveguides for a Fully Functional, RF-in RF-out OBFN

III. FULLY INTEGRATED OBFN SOLUTIONS:

Based on the IO-OBFN technologies presented above, a fully integrated OBFN solution is more preferable than discrete component solution because of the following:

- Fibre-coupled lasers frequently have instabilities in phase and polarisation due to thermal fluctuations and (acoustical) vibrations in the fibre. This causes amplitude fluctuations in the (polarisation sensitive) OBFN.
- Several hundred lasers as individual components will become quite expensive and bulky, whereas an array of several hundred lasers is much cheaper.
- An array of modulators and detectors will be much cheaper and less bulky than many single-components.

For the fully integrated solution, the following aspects have to be taken into account:

1. Any transition from one waveguide platform to the next (e.g., InP to TriPleX$^{\text{TM}}$) will induce fairly high losses due to:
    a. Difference in mode-field diameter
    b. Misalignments
    c. Fresnel reflection originating from the difference in refractive indices
2. The delay section of the OBFN is fairly long
3. An optical power, higher than one currently available single-spatial-mode diode laser can achieve, has to be incorporated

The consequences of these aspects are:

1. It is preferred to only have a single interface between the waveguides; make everything that can be made on InP on a single InP chip, and everything else on a single TriPleX$^{\text{TM}}$ chip.
2. It is preferred to make the OBFN delay lines in TriPleX$^{\text{TM}}$ because of its very low propagation loss
3. It is preferred to have a set of injection locked slave lasers, seeded by a single master laser, such that they all have the same wavelength and phase relation.

Because of extremely low propagation loss and relatively high index contrast, TriPleX$^{\text{TM}}$ is used as best solution for the delay line part of the OBFN, while InP is used as best solution for the active part of the OBFN. Figure 8 show the first-in-the-world attempt to integrate the above named integrated optical platforms to form a working OBFN. Measurements of this device are still being processed.

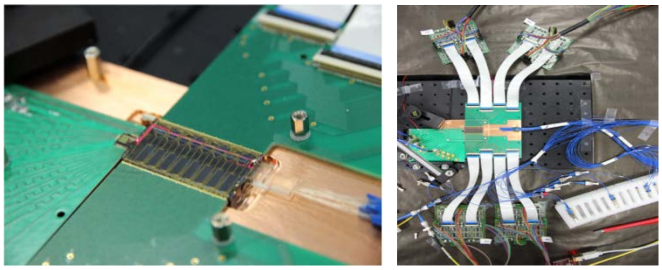

Fig. 8. A Fully Functional, RF-in RF-out OBFN (left), and Fully Functional RF-in RF-out OBFN System (right), Adopted from [12]

B. Summary Comparison between RF-BFN and OBFN

As an overview, a summary comparison of the main parameters for RF-beamforming and IO-OBFN is outlined in Table 7.

Table 7. Summary Comparison Between RF-BFN and IO-OBFN

Parameter	RF-BFN	IO-OBFN	Comments
Size (single direction)	100-500 cm	15 cm	
Footprint (cm2)	1-25 m^2	0.025 m^2	
Mass	10-100 kg	300 g	
Cost	-	+	- = high cost, + = low cost
Vibration Sensitivity	+++	++	+ = less sensitive
Tunability	*	+++	+ = more tunable
RF-crosstalk	--	+++	- = more, + = less cross talk

* is dependent on the layout; a Matrix would not be tunable, a binary tree with phase shifters would be, but not in True Time Delay. The size, footprint and mass are estimated for both the Nolen matrix and the Binary Tree.

IV. CONCLUSIONS:

This paper has outlined optical beamforming concepts that address the reference mission scenarios. The activity investigated nine different OBFN options and the pros and cons of each option was analysed. Two options were identified as promising to be investigated further. Detailed designs of these two options were performed and one of these was elaborated on in this paper. The risks associated with the optical OBFN technology were identified and mitigation actions to address these risks were developed.

Major advantages of optical beamforming are its promise to reduce the mass, power consumption, footprint, and cost of complex beamformers, as well as reduction in effort required for Assembly, Integration and Test (AIT). A typical application of such a system would be the Terabit Satellite system, the subject of a recent ESA study.

This paper has outlined the requirements of a receive antenna using OBFN technology. A transmit antenna incorporating OBFN technology presents additional technical challenges, particularly thermal design. These considerations, however, apply to any transmit array and are not specific to a transmit array connected to an OBFN.

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