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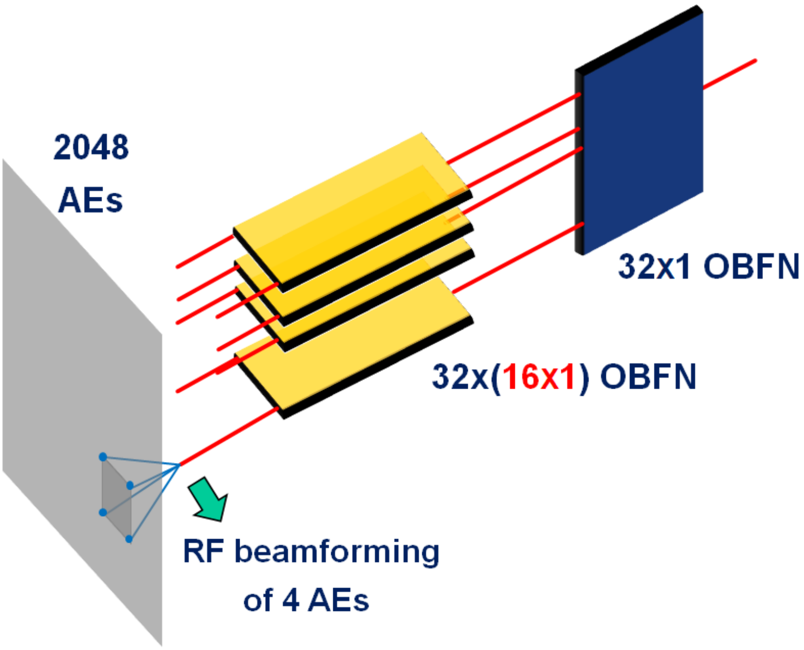
Executive summary

Architectures for K_u-band broadband airborne satellite communication antennas



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Problem area
The need for onboard communication on aircraft is increasing. In the cockpit reliable long distance communication is needed for air traffic communication. The cabin and cockpit crew want to exchange operational information with the staff on the ground. And passengers want to have the same provisions as at home where they have live (satellite) TV reception and broadband internet access. In order to accommodate these needs a broadband satellite link is needed, especially during long distance (intercontinental) flights. Antenna systems operating in L-band are already available but a satcom antenna for K_u-band would provide a higher bandwidth. Therefore a K_u-band broadband phased array antenna is being developed. Phased array antennas with beamforming based on (only) phase shifters is inherently narrow bandwidth. Therefore a beamforming network based on True Time Delays (TTD) is being developed. For this network Optical Ring Resonators

This report is based on a presentation held at the 32nd ESA Antenna Workshop on Antennas for Space Applications, 5 – 8 October 2010. ESTEC, Noordwijk, The Netherlands.

(ORRs) are used as continuously tuneable TTDs.

Description of work

This paper describes different architectures for a broadband antenna for satellite communication on aircraft. First the requirements for such a system are addressed. Subsequently a number of potential architectures are discussed in detail: a) an architecture with only optical true time delays, b) an architecture with optical phase shifters and optical true time delays and c) an architecture with optical true time delays and RF phase shifters (or RF true time delays). The last two architectures use sub-arrays to reduce complexity of the antenna system. The advantages and disadvantages of the different architectures are evaluated and an optimal architecture is selected.

Results and conclusions

An architecture with optical beamforming (based on True Time Delays) for the sub-arrays and RF phase shifters for the beamforming of the elements in the sub-array seems the best option in terms of complexity and performance. At the end of 2010 (the first year of the project) a final choice will be made for the architecture to be implemented. After that, components of the antenna system will be designed, manufactured and measured. The results will be used to verify the validity of the architecture design. At the end of the project the antenna system will be demonstrated in combination with radios and modems developed in the project.

Applicability

The technology developed in this project will not only be of interest for antennas on aircraft but also for antennas on other platforms that need a broadband reception capability (ships, busses, cars).

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Architectures for K_u-band broadband airborne satellite communication antennas

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Summary

This paper describes different architectures for a broadband antenna for satellite communication on aircraft. The antenna is a steerable (conformal) phased array antenna in K_u-band (receive-only). First the requirements for such a system are addressed. Subsequently a number of potential architectures are discussed in detail: a) an architecture with only optical true time delays, b) an architecture with optical phase shifters and optical true time delays and c) an architecture with optical true time delays and RF phase shifters (or RF true time delays). The last two architectures use sub-arrays to reduce complexity of the antenna system. The advantages and disadvantages of the different architectures are evaluated and an optimal architecture is selected.

Contents

Abbreviations

AE	Antenna Elements
AMSS	Aeronautical Mobile Satellite Services
ANASTASIA	Airborne New Advanced Satellite Techniques and Technologies in A System Integrated Approach
BPD	Balanced Photo Detector
CMOS	Complementary Metal Oxide Semiconductor
DVB	Digital Video Broadcast
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
EURIPIDES	EUREKA Initiative for Packaging & Integration of µDevices & Smart Systems
FP	Framework Project
IEEE	Institute of Electrical and Electronics Engineers
IS	Innovation Subsidies
ITG	Informationstechnische Gesellschaft in VDE
LEOS	Laser and Electro-Optics Society
LNA	Low Noise Amplifier
LO	Local Oscillator
LPCVD	Low-pressure chemical vapor deposition
MEMPHIS	Merging Electronics and Micro & Nano-Photonics in Integrated Sysems
MMIC	Monolithic Microwave Integrated Circuit
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
OBFN	Optical Beamforming Network
ORR	Optical Ring Resonators
PAA	Phased Array Antenna
PCB	Printed Circuit Board
RF	Radio Frequency
SANDRA	Seamless Aeronautical Networking through integration of Data links, Radios, and Antennas
TTD	True Time Delays
TV	Television
UK	United Kingdom
WSA	Workshop on Smart Antennas

1 Introduction

The need for onboard communication in aircraft is increasing. In the cockpit reliable long distance communication is needed for air traffic communication. The cabin and cockpit crew want to exchange operational information with the staff on the ground. And passengers want to have the same provisions as at home where they have live (satellite) TV reception and broadband internet access. In order to accommodate these needs a broadband satellite link is needed, especially during long distance (intercontinental) flights. Antenna systems operating in L-band are already available but a satcom antenna for K_u-band would provide a higher bandwidth. Therefore a K_u-band broadband phased array antenna is being developed. Connexion by Boeing was one of the first K_u-band systems that tried to provide such services, however not for the complete K_u receive band. The SANDRA-antenna focuses on a broadband antenna system.

In previous projects like ANASTASIA [5], FlySmart [6] and MEMPHIS [7], parts of this antenna system have been studied. In the SANDRA project [1], a consortium of companies, research institutes and universities will be developing a full scale antenna system which will be tested with aircraft modems and radios at the end of the project (2013).

2 Antenna System Requirements

The downlink frequency bands for aeronautical mobile satellite services (AMSS) in K_u-band and the frequencies of the broadcast satellite service are between 10.70 and 12.75 GHz:

- Aeronautical Earth Stations (AES) receive band 1: 10.70 – 11.70 GHz (primary allocation to fixed satellite service)
- Satellite TV: 11.70 – 12.50 GHz (primary allocation to broadcast satellite service)
- AES receive band 2: 12.50 – 12.75 GHz (primary allocation to fixed satellite service).

The total K_u-band antenna system consists of an antenna front-end and a beam forming network. The output of the antenna system is connected to a DVB-S receiver in case of reception of satellite television. A beam forming network with tuneable True Time Delays (TTD) will be used to guarantee broadband reception (2 GHz bandwidth). The antenna elements used are stacked patch antennas which also have the required bandwidth of 2 GHz. The required gain of the phased array is about 37 dB and the beamwidth is in the order of 2 degrees. Therefore the antenna front-end consists of at least 1600 antenna elements. Depending on the maximum scan angle of the array antenna, the number of antenna elements may have to be increased. A modular approach is used for the build-up of the total array aperture: the antenna is subdivided in (at least) 25 tiles of 64 antenna elements (8x8 antenna elements).

For a mobile platform polarisation tracking is needed. However, the first demonstrator which will be realised for the SANDRA project will contain only horizontal and vertical polarisation as is needed for a fixed ground terminal.

The future antenna system will use a tracking system that will steer the beam of the antenna to the geostationary satellite, based on the satellite position and the aircraft position and attitude. Probably two antennas (one on each side of the aircraft fuselage) will be used to be able to operate the system also at high latitudes (e.g. during transatlantic flights). Earlier studies have shown that in the case of two antennas, the scan angle of each antenna can be limited to 45 degrees.

3 Antenna Architectures

In the current phase of the SANDRA project different antenna architectures are being studied. In general, the beamforming of the antenna can be implemented as an optical system, an RF system or as a hybrid system where RF phase shifters are used for the sub-apertures and TTDs are used for the main beamforming. Each of these types of beamforming has its own (bandwidth) performance. Apart from performance considerations, the complexity and cost of the demonstrator antenna are also important.

A number of different architectures can be defined for broadband beamforming:

1. Beamforming with only RF phase shifters (no sub-arrays).
2. Beamforming with only optical phase shifters (no sub-arrays).
3. Beamforming with optical TTDs (no sub-arrays).
4. Beamforming with optical TTDs for the main beamforming and optical phase shifters for the sub-arrays.
5. Beamforming with optical TTDs for the main beamforming and RF phase shifters for the sub-arrays.
6. Beamforming with optical TTDs for the main beamforming and RF TTDs for the sub-arrays.

Architecture 1 and 2 are not suitable for a broadband application because phase shifters are inherently narrowband. Option 3, an architecture with only optical TTDs, is discussed in section 3.2. Option 4, where optical phase shifters are used for the sub-array, is addressed in section 3.5. Finally, option 5 and 6, where RF phase shifters or TTDs are used, are discussed in section 3.6. In section 3.3 the use of not continuously tuneable TTDs is discussed. Section 3.4 addresses the difference between using phase shifters or TTDs for the beamforming of a sub-array.

As an outcome of earlier studies [8, 9, 10], it was decided to use optical TTDs for the main beamforming network. Subsequently a choice had to be made whether to use only TTDs (to enable broadband performance) or to make a hybrid system with both TTDs and phase shifters.

3.1 The Optical Beamforming Network (OBFN)

Optical Ring Resonators (ORR) can be used as True Time Delay (TTD) elements [2]. In this section the principle functioning of ORRs is explained. The peak value of the delay of an ORR is inversely proportional to the bandwidth. This imposes a trade-off between the highest delay and the maximum bandwidth that can be obtained. To overcome this, several ORRs can be cascaded, where the total group delay response is the sum of the individual ring responses. This is illustrated in Figure 1 and Figure 2.

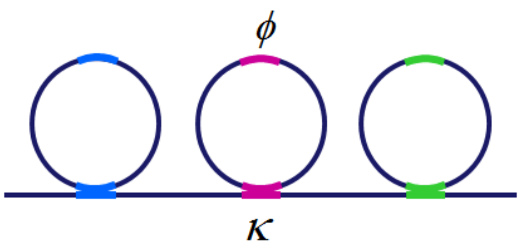

Figure 1 Cascaded optical ring resonators delay

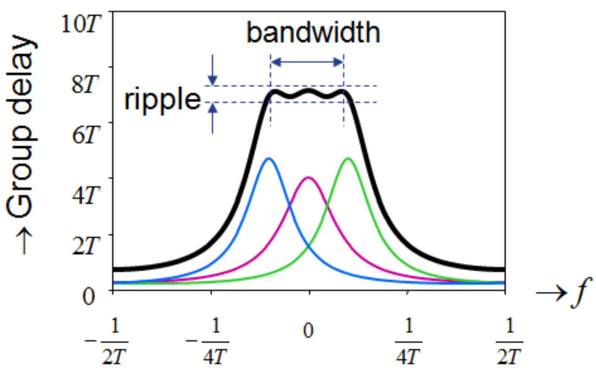

Figure 2 The group delay response of three cascaded ring resonators

A full OBFN is obtained by combining the ORR based delay elements with power splitters and combiners. An example of a 16×1 OBFN is shown in Figure 3. It is based on a binary tree topology, consisting of four sections, sixteen inputs and one output. In this particular case a total of twenty rings are involved. The rationale for using such a topology is that, for a linear PAA, increasing delay tuning ranges are required for the sixteen possible paths through the OBFN, where the upper path (from input 1 to the output) is considered as the reference path.

The details of the OBFN design can be found in [3]. A delay as high as 1.2 ns over a bandwidth of 2.5 GHz has been demonstrated with a cascade of 7 ORRs, in an 8x1 optical beamformer. For comparison, 1 ns is approximately 30 cm of propagation distance in vacuum.

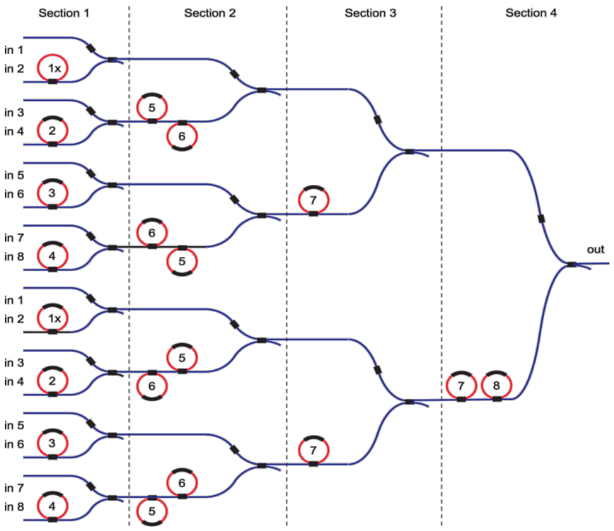

Figure 3   Architecture of an 16x1 optical beamforming network

3.2 Phased array without sub-arrays

The first architecture that was considered is a phased array without sub-arrays: every antenna element is connected to the beamforming network (Figure 4).
The advantage is that the RF front-end is less complex. No RF-combiner is needed to combine the output of the antenna elements of the sub-array and no core-chip with RF phase shifters is needed. Therefore less space is needed on the front-end printed circuit board (PCB). In addition the RF-losses are lower because no combiners or phase shifters are used.

However, the disadvantage is that every antenna element has to be connected to the OBFN by means of an optical modulator. Therefore the total number of modulators per tile is very high. In addition the OBFN chip will become very complex (64 channels chip). This imposes a high risk due to a lower yield. In case of a 64 channel chip the number of tuning elements required is high and also many control lines are needed. The connection between the RF PCB and the optical PCB will also become more complex due to the fact that 64 connections are needed.

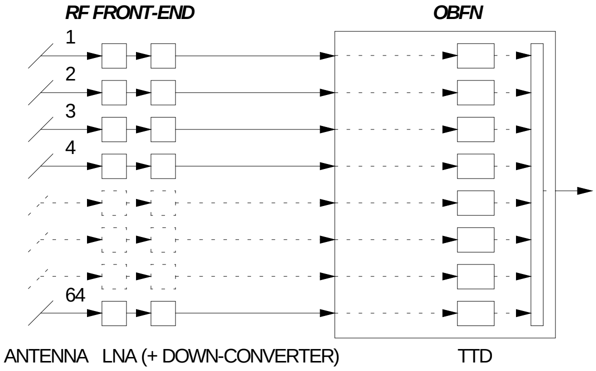

Figure 4   Schematic overview of a full optical beamforming architecture with TTDs

3.3 The use of digital True Time Delays

The OBFN uses continuously tuneable TTDs. In the MEMPHIS project [7], a small study was carried out to see whether a combination of optical TTDs and digital RF TTDs could be used (switched delay lines). Therefore the Array Factor of a Mobile Ku-band Receive Array was analysed (in the range 10.70-12.75 GHz). In particular the directivity, the null-to-null beamwidth, the 3 dB beamwidth and the sidelobe level were computed for an array antenna with 1600 antenna elements, divided in 25 tiles of 8x8 antenna elements. Each tile was subdivided in 16 sub-arrays of 2x2 antenna elements. The beamforming of all the sub-arrays was done with optical TTDs. The elements in a sub-array were controlled by digital TTDs. As a baseline the effects of using an 8 bit TTD for the sub-array of 2x2 antenna elements was simulated. The 8 bit TTD comes close to a continuously tuneable delay. Subsequently, the same simulation was carried out with a 3 bit TTD. The simulations were carried out for different steering angles of the phased array.

As an example, the directivity and beamwidth are presented. As shown in Figure 5, the difference in directivity is maximum 0.3 dB between the 3-bit and the 8-bit TTD. In Figure 6 the difference is shown for the 3 dB beamwidth between both types of TTDs. The difference is less than 0.003 degrees. From the study it can be concluded that a 3 bit TTD (8 levels) would be sufficient for this purpose.

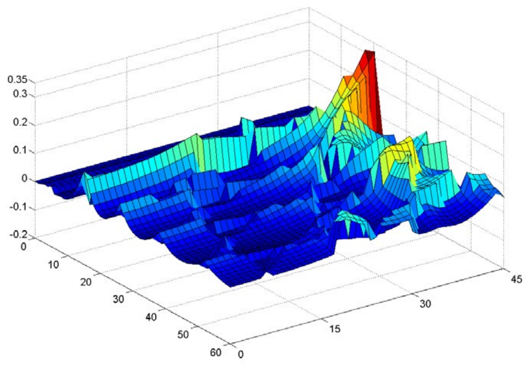

Figure 5 Maximum directivity at 10.7 GHz. Difference between 8 bit and 3 bit True Time Delays

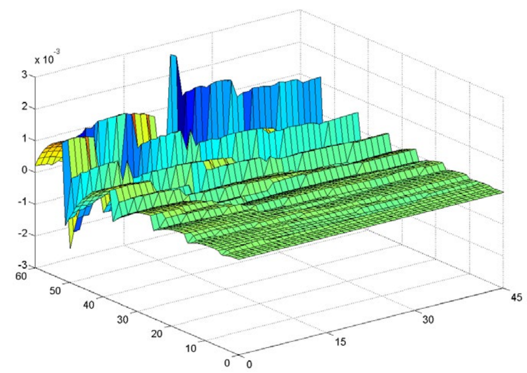

Figure 6 Simulated 3 dB beamwidth at 10.7 GHz. Difference between 8 bit and 3 bit True Time Delay

3.4 True Time Delays or Phase Shifters for local beamforming

Another small study was carried out to see whether the beamforming for the 2x2 sub-array should consist of TTDs or could be done with phase shifters. The risk of using phase shifters is that beam squinting may occur if the bandwidth is too large. This will not happen if TTDs are used. The study was carried out for the same antenna as presented in the previous section, having sub-arrays of 2x2 antenna elements. Figure 7 show the difference between array factor in case continuously tunable phase shifters are used and for the case continuously tuneable true time delays are used. In Figure 8 the use of digital phase shifters for the sub-array is shown. This figure shows that using a 3 bit digital phase shifter provides a sufficient accurate radiation pattern.

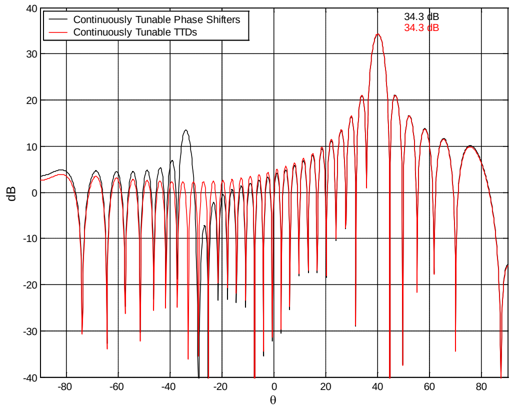

Figure 7 Directivity of the phased array antenna at 10.7 GHz, using continuously tuneable phase shifters or continuously tuneable true time delays for the 2x2 sub-arrays. In this case the steering angle is 45 degrees

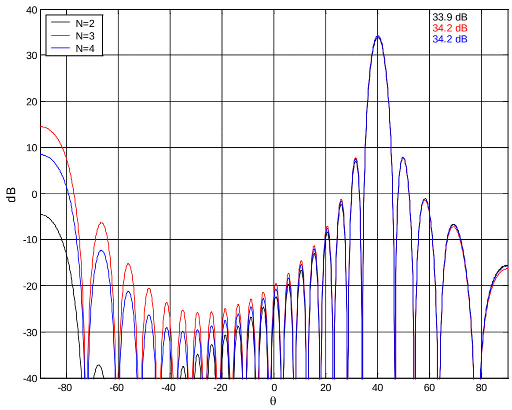

Figure 8 Directivity of the phased array antenna at 10.7 GHz, using digital phase shifters for the 2x2 sub-arrays. In this case the steering angle is 45 degrees

3.5 Phased array with sub-arrays and Optical Beamforming (optical phase shifters and optical TTDs)

Given the complexity and cost of an array antenna without sub-arrays, the design of an antenna with sub-arrays (and local beamforming) was investigated (Figure 9). This design consists of 16 sub-arrays per tile, each with 4 antenna elements (2x2). Earlier analysis had indicated that local beamforming was needed; otherwise grating lobes would be introduced in the radiation pattern. For this first potential architecture with sub-arrays continuously tuneable optical phase shifters are used to do the local beamforming for the sub-array.

The advantage of this architecture is that the OBFN is less complex compared to a full optical beamforming network. Also the heat dissipation is less when compared to a full optical TTD. Moreover, no RF phase shifters are needed which means less RF-losses.
The disadvantage is that still many (64) optical modulators are needed per tile and that still 64 connections have to be made between the RF PCB and the optical PCB.

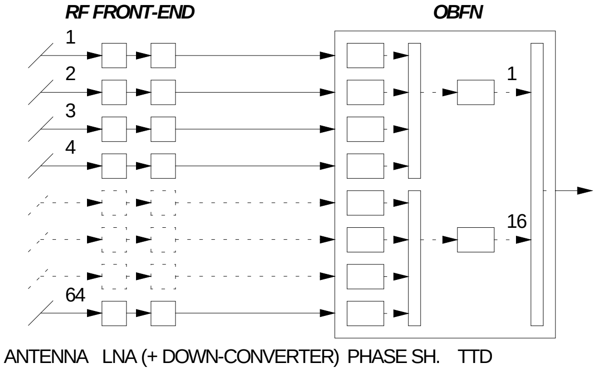

Figure 9 Schematic overview of an optical beamforming architecture. TTDs are used for the beamforming of the sub-arrays. Optical phase shifters are used for the beamforming of the elements in the sub-array

3.6 Phased array with sub-arrays, MMIC front-end and Optical Beamforming (RF phase shifters/TTDs and optical TTDs)

The final architecture uses also 2x2 sub-arrays. In contrast to the previous architecture, this architecture uses local RF-beamforming. MMICs are used to steer the antenna elements of the sub-arrays and the OBFN is used to steer all the sub-arrays (Figure 10).
The advantage is that the complexity of the OBFN is much lower than in the previous architectures. The OBFN chip will have only 16 channels per tile which has shown to be feasible in other projects. This implies that less optical modulators are needed and that also the number of connections between the RF-board and the optical boards is less.
Of course this architecture also has some disadvantages. Since RF phase shifters and combiners are needed, the losses in the front-end are higher and more space is needed on the RF PCB. Also extra control lines are needed for the phase shifters.

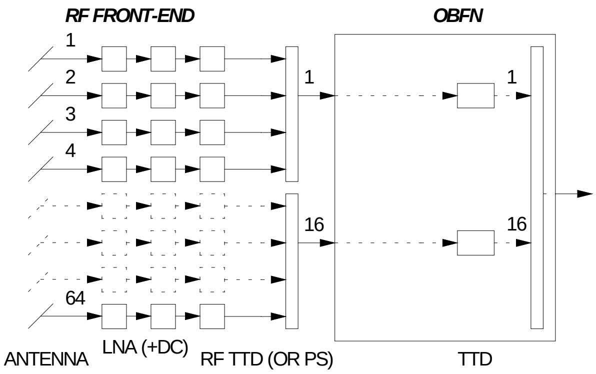

Figure 10 Schematic overview of hybrid beamforming architecture. Optical TTDs are used for the beamforming of the sub-arrays. RF TTDs or phase shifters are used for the beamforming of the elements in the sub-array

3.7 Down-conversion before or after optical beamforming

The Ku-band signal will need to be down-converted somewhere in the antenna system before the output of the antenna. Down-conversion is needed in order to be able to connect a long antenna cable; otherwise the losses in the cable would be too high. Most commercial DVB-receivers have an L-band input. The question is: what is best stage of the antenna system to do the down conversion, before or after the beamforming? An architecture with down-conversion before the optical beamforming network seems the most promising.

This option has the advantage the optical modulators are low speed (L-band) modulators instead of high speed (K_u-band modulators). If the down-converter is part of the RF-front it is also easier to have low noise amplifiers with a high total gain because the required gain can be distributed over both K_u-band and L-band. In this case the connection between the RF-board and the optical board is less critical because it is at L-band frequencies instead of K_u-band. However, if standard connectors are used for the connection between the two boards they will be larger at L-band frequencies.

The disadvantage of down-conversion before optical beamforming is that in the OBFN a large optical sideband filter is needed. Moreover a dedicated local oscillator (LO) distribution network is needed.

3.8 Selected architecture

Based on the previous considerations for the different architectures, the architecture selected for demonstration is the architecture with 2x2 sub-arrays, local RF beamforming and down-conversion before optical beamforming. This architecture is believed to provide the best performance and the lowest cost and complexity.

The complete optical beamforming architecture is shown in Figure 11. This is a two-level modular architecture where two stages of optical beamformers are used. In Figure 11A, the phased-array antenna structure is depicted. It consists of N number of antenna tiles (here N=24 is depicted for illustrative purpose only), where each tile consists of 64 Antenna Elements (AEs) (the yellow squares in Figure 11B). Thus the total number of AEs in the system is 64xN. A monolithic microwave integrated circuit (MMIC) beamforming will be implemented to delay and combine the signals from 4 neighbouring AEs. This is illustrated by the red squares in Figure 11B. This means that each tile will not have 64 RF outputs but only 16 RF outputs. These outputs will feed a 16x1 optical beamforming network (OBFN) as shown in Figure 11C. The number of 16x1 OBFNs needed is equal to the number of antenna tiles, which is N.

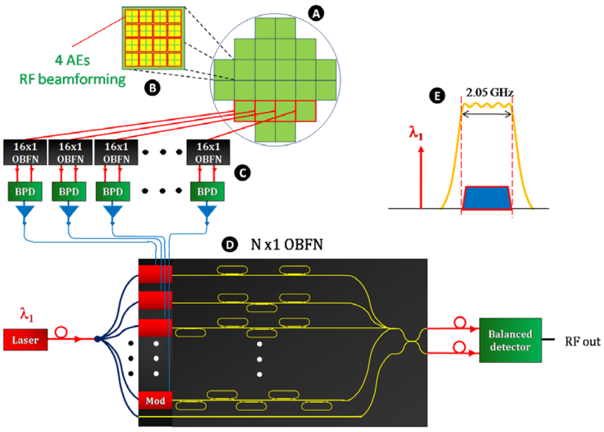

Figure 11   The complete optical beamforming system

The 16x1 OBFN consists of a laser diode, 16 low noise amplifiers (LNAs) driving 16 optical modulators, a 16x1 optical beamforming chip and a balanced photodetector (BPD) to restore the RF signal. The RF output of the BPD is then amplified by a second-stage amplifier before being fed to the modulator RF inputs of the Nx1 optical beamformer, as illustrated in Figure 11D. This beamformer delays the received signals from the first stage beamformers (Figure 11E) and combines them. Here we consider RF signals with a frequency range of 10.7 GHz to 12.75 GHz, hence a 2.05 GHz bandwidth.

4 Future Work

This paper presents different architectures for broadband beamforming for satellite communication. An architecture with optical beamforming (based on True Time Delays) for the sub-arrays and RF phase shifters for the beamforming of the elements in the sub-array seems the best option in terms of complexity and performance. At the end of 2010 (the first year of the project) a final choice will be made for the architecture to be implemented. After that, components of the antenna system will be designed, manufactured and measured. The results will be used to verify the validity of the architecture design. At the end of the project the antenna system will be demonstrated in combination with radios and modems developed in the project.

The phased array antenna with the proposed architecture will be built by a consortium consisting of University of Twente (responsible for the optical beamforming network design), Lionix BV (responsible for the design and manufacturing of the optical beamforming chip), ACREO (responsible for the design and manufacturing of the optical modulators), IMST (responsible for the design of the RF front-end), EADS IW (France) and NLR (responsible for the design of the phased array antenna) and Cyner B.V. (responsible for the manufacturing of the antenna and RF PCBs). Alenia Aeronautica will assist in deriving the environmental requirements for the airborne antenna system. Thales Aerospace (UK) will be managing the project.

5 Acknowledgement

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