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Beam-Forming methods – Final Report

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Abstract

This document synthesises the information collected on various beam-forming techniques, to clearly identify advantages and drawbacks of each techniques and propose a short list of still remaining critical points for each beam-forming techniques. Priorities in future researches related to beam-forming networks are then pointed out

Also are analysed advantages and drawbacks of beam-forming techniques as applied to various applications and domains. Qualitative synthesis tables are set-up, and a general “help for trade off” tool is presented in annex of this document

“Geographical maps” of on-going research in various laboratories and companies are presented in order to show the complementary distribution over Europe, and to help in identifying potential future collaborations (for instance, for building STREPs or FETs in answer to E.C. calls in relevant domains).

Keyword List

Beam forming Network, Reflectarray, Passive Arrays, Analogue Controllable Arrays, Digital Controllable and Adaptive Arrays, Microwave Photonics beam-forming arrays

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ACE WP 2.4-2 – "Beam-forming methods: Deliverable D5 - Final Report

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1 INTRODUCTION

1.1 Description of Work – ACE WP 2.4-2

The description of work that was given in the Technical Annex [128] is repeated here for convenience:

The aim of this work package (for which the present deliverable is the final report) were :

1. Synthesise the present state-of-the-art on Beamforming (BF) techniques, including :
   - Analogue BF : for Direct Radiating Array (DRA) by controlling phase shifters and variable-gain amplifiers;
   - Reflectarrays antennas are a specific case where RF signal distribution is performed in free-space, and phase control on the reflecting cells,
   - Digital BF, after analogue to digital conversion (ADC) : this technique offers more flexibility (adding "adaptive" algorithms for re-shaping in real-time the various beams, it leads to so-called "smart antennas"); but for broadband applications, it needs very fast ADC's, which cost & DC consumption should be considered
   - Optical BF : especially for very large bandwidth, it may be a performant solution to modulate optical carriers and use them for down or up-conversion of the RF signal, control dynamically phase and amplitude, possibly use very fast switching properties proven in terrestrial optical routers.

2. Exchange knowledge and experience among the NoE participants from previous or on-going European projects, and published results in other countries, the main advantages and drawbacks of each technique, for the various categories of antenna applications.

3. Organise the work-sharing between the participants, to investigate new BF techniques, or jump new steps in the existing ones.

4. In complements to internally self-funded researches, propose the public institution or agencies, able to fund long term researches, a short list of the work to be launched to go ahead in BF for active antennas. Form teams to answer the relevant calls from the European commission.

Furthermore, final report D5 on architectures of Active Arrays must summarise potentialities and still remaining critical aspects of various beamforming techniques, includes some outputs of the 2 other work-packages of the same "Array Antennas" activity, WP2.4-1 and 2.4-3, as we worked in tight collaboration.

1.2 Participants

The participating entities in this work package are the following (reference numbers as in the Consortium Agreement and Technical Annex[128]]):

No.	Organisation	Short Name	Country
7	Alcatel Space	Alcatel	France
10	Thales Airborne Systems	TAS	France
14	Technische Universität Darmstadt	TUD	Germany
15	Deutsches Zentrum für Luft- und Raumfahrt E.V.	DLR	Germany
27	Universidad Politecnica de Madrid	UPM	Spain
28	Universidad Politecnica de Valencia	UPV	Spain
31	Swedish Defence Research Agency	FOI	Sweden
33	Saab Ericsson Space AB	SAAB ERICSSON	Sweden

Table 1-1: Organisations participating to WP 2.4-2.

1.3 Contents of this Deliverable D5

In the previous deliverable D4, has been related in details the outputs of the important effort put on collecting information about existing arrays, by mean of questionnaires filled by all partners, describing existing arrays properties Questionnaires have been used for analysing advantages and drawbacks of BF techniques, that have been resumed in a preliminary synthesis table.
In this aim, subgroups corresponding to different beamforming techniques have been constituted. They are as follows :

- 1/ Reflectarrays. This group is coordinated by UPM (J. Encinar), with Thales, Alcatel Space, TUD, and Politecnico di Torino

- 2/ Passive Feeding/Combining Network : This group is Coordinated by Saab Ericsson (H. Ekstrom), with DLR, UKARL, TUD, and UPM.

- 3/ Analogue Controlable Beamforming Networks : This group is coordinated by Alcatel Space (G. Caille) with EMW and Thales

- 4/ Digital Controlable/Adaptive Beamforming : coordinated by Alcatel Space (C. Guiraud) with FOI, DLR, Ericsson, Thales.

- 5/ Beam Forming based on microwave photonics : On this particular subject, a single questionnaire has been received. UPV provides here a synthesis based on its experience.

Furthermore, analysis of each application requirements has been performed, for each of following domains :

- Base-station antennas
- Commercial and civil Radar applications
- Spaceborne Array Antennas
- Defense Radar Applications
- User terminal Arrays

The aim of this present document is :

- To synthesise information collected on various beamforming techniques to clearly identify advantages and drawbacks of each techniques and t propose a short list of still remaining critical points for each beamforming techniques, and identify what should be the priorities in future researches related to beamforming networks.
- To present a “geographical map” of on going research in various laboratories and companies. This should help future collaborations (besides those already existing), especially to build STREPS or FETs in answer to the relevant E.C./IST calls.
- To analyse advantages and drawbacks of beamforming techniques, when applied to various applications and domains. Synthesis tables are proposed and a general “help for trade off” tool is presented in Annex (§5) to this document

2 SYNTHESIS ON VARIOUS BEAMFORMING METHODS, ADVANTAGES AND DRAWBACKS, REMAINING ISSUES.

2.1 Reflectarrays

2.1.1 Synthesis on Reflectarrays technology

The different reflectarray concepts can be classified in two sub-groups, passive and reconfigurable reflectarrays.

For passive reflectarrays, different concepts have been demonstrated for phase control, such as patches with attached stubs of different lengths, sequential rotation, patches of variable size in single or multiple layer, etc. The configuration based on stacked layers with patches of variable size as phase-shifter is very promising because the following advantages:

- Reduction of cross-polarisation, compared with stub loaded patches and compared with offset reflectors.
- A high efficiency of the reflective surface is achieved, with dissipative losses from 0.2 to 0.5 dB.
- Simple manufacture by using photo-etching techniques.
- Bandwidth improvement is achieved by stacking several array layers (two or three) and performing optimisations in a given frequency band.
- Allows simple design of contoured beam antennas with the advantage of eliminating the custom moulds used for manufacturing shaped reflectors in space applications.

On the other hand, the most significant inconveniences of this passive technology are:

- Bandwidth larger than 10% is difficult to achieve for large antennas (> 65 wavelengths).
- In all the analysis and design techniques, the reflectarray is assumed in the far field of the feed-horn, which is not always the case.
- For analysis and design, mutual coupling among elements is only taking into account assuming local periodicity approach, using the infinite array model.
- No possibility of beam scanning or reconfigurability.

In reconfigurable reflectarrays, the beam can be reconfigured or scanned by introducing controllable phase-shifters (using switches, variable capacitors, tuneable dielectrics, MEMS, etc) at the printed elements (or at a subarray level). From the several concepts demonstrated for reconfigurable reflectarrays, those based on switches (diodes or MEMS) at element or subarray level are selected as the most promising, because offers the possibility of scan or reconfigure the beam at moderate cost and complexity. Reflectarrays based MEMS is a very promising technology, because dissipative losses are much lower than in diodes. However MEMS are not a fully mature technology and there are still some technological bottlenecks that must be addressed in future research work as:

- Precise modelling is required.
- Reliability in case of very numerous phase-shifter elements.
- Packaging compatible with radiating element in the reflectarray.
- Complex bias control for large number of elements.

Because the technological interest of MEMS in reconfigurable reflectarrays, a study was carried out in collaboration with the Network of Excellence AMICOM, in which a deliverable has been issued with a review of the most suitable applications and architectures for MEMS based reflectarrays. As a result of this collaboration, three small projects have been proposed for designing manufacturing and measuring reflectarray demonstrators using different MEMS architectures, to be developed during ACE-2 and AMICOM.

2.1.2 Points to by studied in priority:

The analysis of advantages and critical points for reflectarray technology identified in this activity (see Deliverable D4 for more detail), suggests that the following points require a further research work, in order to improve the electrical performances in reflectarray antennas:

- Analysis, design and demonstration of new phase-shifter elements for reflectarrays, in order to improve the electrical performances (low losses, low cross-polarisation, increase bandwidth), and to simplify manufacturing process.
- Different approaches for a more accurate analysis and design of reflectarrays. One way of improvement is to consider the real field radiated by the feed, which is incident on each reflectarray element. This point is particularly important when the reflectarray is not in the far field region of the feed-horn. Another way of improvement in the analysis techniques is to analyse the whole reflectarray, including the horn, by a full wave technique. This problem will be proposed as a benchmark for collaboration with the activity WP1.1-2 during ACE-2.
- Demonstration of suitable new architectures for beam reconfigurability, as for example:
  - Controllable phase-shifter elements based on MEMS
  - The use of non-linear tuneable dielectrics as Ferro-electric materials or Liquid Crystals.
  - Evaluate and demonstrate reconfigurability by control at subarray level.

2.2 Passive Feeding/Combining networks

- **From technological point of view**, the choice is between 2 main options for a passive BFN: waveguide or printed circuits; both are mature for many applications. A subgroup of printed circuits is the suspended technology for lower loss. For low frequencies coaxial guides, squareax, is a subgroup of the waveguide technology.

Generally there is a trade off between:

- on one hand low loss and high analysis accuracy of waveguide technology. For low frequencies coaxial guides “squareax” is a subgroup of the waveguide technology
- on the other hand low volume and mass, and larger bandwidth of printed circuits technology. For highly complex structures (i.e. structures with numerous couplers and/or crossing points), waveguide networks are difficult to build.A subgroup of printed circuits is the suspended technology for lower loss.

Priority for study would be development of suspended techniques with rather low losses, moderate bandwidth and low mass. Both technological aspects (loss, thermal properties) and modelling (RF and thermal) are important to improve. Particularly in high performance applications, e.g. space antennas, the relatively high uncertainty in models of printed circuits compared to the accuracy of waveguide models is critical. This is due to a more complex and less well defined surrounding of printed circuits compared to the closed waveguide structures. Also printed circuit technology generally including several materials with different thermal properties has inherently thermo mechanical limits to reach the tolerances.

- **From architecture point of view**, there are also 2 main options:

- <u>a single fixed beam</u> may be generated by a quite simple passive BFN, using either corporate feed principle, or series-fed …letting aside some very specific implementations such as radial distribution within a flat “cheese-like box”.

- <u>several fixed beams</u> may also ge provided by passive networks, with some limitations: the angular separation between the beams must be sufficient, and the passive network should generate “orthogonal” complex excitations. This is possible through Butler or Blass matrices, of using a space-constrainted feed such as a Rotman lens (see Deliverable D4 for more details).

The latter option appears to be very promising for several applications such as:

- simultaneous multiple decoupled beams in a base-station;
- a narrow switched between several (4,8…) positions in an anti-collision automotive radars.

For such large-market application, the main topic fo new researches and developments appear to find simple (so low-cost) while efficient solutions. Often their performance may be significantly increased if associating suited signal processing, for instance for the 2 applications mentioned here-above.

2.3 Analogue Controllable Beamforming Network

2.3.1 Synthesis of associated architectures & technologies

The description presented in §8.1 of Deliverable D4 has shown that within the concerned category, the solutions are rather diverse:

A/ Single-beam passive phased array is the simplest; the same beam-former can operate either in transmit or receive:.

- It uses a low-loss combiner (RX[1] case) or divider (TX case)
- the controllable phase-shifters are based either on variable magnetisation of ferrite material partially filling a waveguide, or on a circuit comprising several "bits" (180°, 90°, 45°... phase-shifts, obtained by switching On/Off PIN-diodes or MEMS switches inserted in a suited small circuit network).

B/ Single-beam active phased array: it includes amplifiers directly connected to the radiating elements, which main property is to minimise the RF-loss impacting the link budget. Sub-categories are:

B1) Transmit-only case: the mentioned amplifiers are SSPAs delivering moderate power, mostly in a single MMIC chip.

B2) Receive-only case: LNAs are connected to the radiating elements, which maximises the antenna figure of merit (G/T).:

B1) Alternate TX/RX active arry for radar: both SSPAs and LNAs are implemented: the 2 ways are swithed at the pulse repetition frequency.

C/ Multi-beam active phased array: it uses a single SSPA or LNA per radiating element. But the beam-fomer located behind has P (beams number) x N (elements number) controllable phase-shifters, and the suited network of splitters and combiners

Notice that in **B** & **C** active architectures, the priority is given to compactness and low-cost for the BFN parts; higher RF-losses can be afforded than in the passive **A** case, because here they are "hidden" by the amplifiers gain.

D/ "Semi-active"array is a term that may be used in 2 very different senses according to the application; in both cases it concerns quite specific architectures, partially derived from the previous ones.

- for radar, it means an hybrid architecture: a passive solution in TX, and an active in RX, sharing the same radiating elements
- for telecommunication from an axi-symmetrical array, it means placing Butler-type matrices, which transforms the phase-law corresponding to each beam (in the ist part of the BFN, in front of SSPAs) into an amplitude (and phase) law, which allows to make the illuminated (alias "activated") elements to "turn around the array".

2.3.2 Main advantages & drawbacks – critical items for future Research

a) If speaking in a general way, whatever is the detailed solution (among those recalled in §2.3.1), **the main advantages** of analogue controllable BFNs are:

[1] For the meaning of all abbreviations, please see the last paragraph of this document "Acronyms"

- good maturity: principles and various implementation ways are known from decades (pushed at the beginning by defense radar funding)
- accurate beam-forming, while adjusting the precision of the phase-shifters to the mission requirements, implementing precise path-by-path calibration, then compensation of errors by some tuneable devices for amplitude, and via controllable phase-shifters.
- The multibeam capability, with independent control per beam, provided that the phase-shifters number is multiplied by the number of beams.
- Among numerous RF-chains working in parallel, some failure may occur with only a moderate performance decrease. Such "graceful degradation" is of great advantage: it avoids "cold redundancies", that are compulsory in other antenna types for all applications requiring a long life-time without repairing; so in such non-arrayed architectures, one's needs to build many more units than strictly necessary for the mission, and the redundancy switches add RF-loss.

b) The critical items, and the ways to overcome them in the future (marked **in bold blue**), are listed here-after:

b1/ the complexity of the beam-former is proportional to P (number of beams) x N (number of radiating elements). This complexity factor impacts many parameters: mass, volume and cost mainly.

The solution is to go **towards more integrated technologies**;

- an example of a compact assembly for a (3 beams) x (48 radiating elements) has been presented in §8.1 of Deliverable D4. controllable devices are MMIC chips, placed in micro-packages above a multilayer circuit which performs all the divider/combiner functions

- however, this is a high-tech solution, implemented for a satellite array, so for the moment expensive. It should be assessed whether automatic processes could make similar solutions affordable for mass-market applications.

b2/ The operating bandwidth of such arrays is limited to 10-20%, due to the matching bandwidth of each device, and to intrinsic phenomena that the phase-law allowing to scan any beam is frequency dependent.

If a larger instantaneous band is required, the only solution seems **to replace phase-shifters by controllable TTD** (True Time Delays); but the latter are bulky, except if the full beam-former is implemented in microwave photonics technology: its principles have been described in details in §10 of Deliverable D4; but there are still research & development to be performed for reaching low-cost industrial products with a large number of controllable paths.

If the instantaneous bandwidth is moderate, but frequency agility is required over a larger band, the solution is to **re-compute and apply new phase-commands when the frequency hops**.

b3/ The DC consumption of active arrays is still a handicap, for several reasons:

- because the number of low-level amplifying stages (LNA in RX antennas; "drivers" in TX antennas) is multiplied by the number of paths.

  The solution is to go further in **the development of new solid-state technologies**, with very low consumption, improved Noise Figure, etc (hetero-junctions; new materials such as InP in place of GaAs …)

- For transmit antennas, the DC-to-RF efficiency of numerous SSPAs delivering a moderate power, put in parallel, is lower than that of a centralised TWT, or even often than that of a single high-power SSPA.

  The solution are :
  - first, to implement **innovative antenna architectures** allowing uniform amplitude distribution (for optimising SSPAs at a single point), while low side-lobes: array thinning, irregular lattice …
  - secondly, to progress in the field of **new technologies providing highest SSPA efficiency**, at moderate cost ("wide bad-gap" transistors such as SiC, GaN .. may be biased at much higher voltages than classical GaAs & SiGe, and are promised to withstand higher junction temperature without failuire).

2.4 Digital Controllable Adaptive Beamforming

2.4.1 Synthesis on Digital Controllable Beamforming Networks technology

Digital Beamforming on receive consists in digitising radiating elements (or subarrays) signals, and then operate on digital support an operation that is equivalent to RF Beamforming. On transmit, signals coming from several beams are weighted and summed before amplification in order to realise beamforming on digital support. Digital Beamforming can be associated to direct radiating array, or focal array fed antenna or other type of array antenna.

In most cases, beamforming is performed weighting each input (radiating element port on receive, beam port on transmit) by a complex weight , then sum the signals. This is known as “1D beamforming”. In particular cases, this can be simplified by using pre-forming, or by using specific algorithm like FFT beamforming. When required, computation and real-time update of weighting coefficient can be performed by analysing and process received signals, and in order to comply with specific conditions. It is then talked about adaptive beamforming. If required by the relative bandwidth wideband processing coupling time and spatial processing can also be applied.

Main advantages of digital beamforming are related to the flexibility of realising beamforming by digital processing. In particular :

- Beamforming coefficients can be easily modified, bringing a great flexibility in beamforming.

- Beamforming can be coupled and mixed with other digital processing , in order to associate beamforming and time processing. This for example allows to:
    - Introduce space-time processing for radar application,
    - For multibeam applications, associate frequency resource management to spatial resource management, by allocating proper frequency band to various beams.

- Sampled signals can be observed and used for adaptive processing, or annex processing (calibration…) with no induced degradation on on-going communications. The use of signal processing associated to such an antenna allows improving gain and C/I performances for a given antenna design, or to relax antenna dimensions for a given specification. As a consequence, it allows in some case increasing the capacity of communication signals, either by increasing frequency reuse rate, or by improving guaranteed performances.

- Furthermore, complexity of digital beamforming is less impacted by the number of inputs/outputs than analogue beamformer. Moreover, no constraint is imposed on beam orthogonality because there are no losses directly related to beamformer network itself. Use of digital beamforming network then allows an increase in the number of beams, and in the reuse rate of each radiating element on receive. This has an impact on coverage definition and on radiating panel design.

- Continuous evolution of digital technology let expect constant improvements in processor performances, mass and consumption.

Main difficulties and drawbacks related to digital beamforming concern following points:

- Down conversion of radiating elements signals.
    - The number of digitised channel should be reduced in order to reduce as much as possible the number of downconversion/ upconversion device, then reduce mass and consumption. This can be done by proper definition of subarrays and/or a first analogue beamforming stage
    - However, use of digital beamforming on dual polarisation, or on multiple separated bandwidth would imply a multiplication of downconversion/ upconversion device, which is not compatible with present state of the art.

  - The bandwidth of signals has also an impact on down/up conversion device architecture definition and performances, in particular on anti-imaging and anti-aliasing filters definition. This can impact the down/up converter architecture, leading to several stages of down/up conversion, then impact strongly mass and consumption related to down/up converters.
  - Use of photonic technology and MMIC makes it possible to foresee very high level of integration. However, analysis concerning thermal aspects are still pending.
- Signal digitalisation, especially for wide absolute bandwidth signal, can be very consuming. This is the case for wideband communication signal, but also for pulse radar with very short pulses implying very wide bandwidth signals.
- Computational burden and processor definition is a delicate point especially when dealing with wide band signals. In particular, it has been quoted than interconnections definition, and then detailed design of processor can have a strong impact on processor mass and consumption.

Mass and consumption related to down conversion and signal processing are then a big issue related to digital beamforming antennas. However, this apparent drawback must be in reality estimated at system level. As a matter of fact a digital beamforming antenna providing digitised output can not be strictly compared to an antenna providing RF output, still to be sampled if necessary.

Concerning transmit antenna, high power amplification issue are still remaining but are not strictly related to the use of digital beamforming.

2.4.2 Points to by studied in priority

Critical points identified for digital beamforming technology suggests that following points should be further studied in next few years :

- Integration of down-conversion and up-conversion devices, associated to proper analysis or thermal constraints related to the integration of receiving/transmit device behind the radiating panel
- Integration of high bandwidth digital beamforming within high rate digital processor
- Assessment of the advantages of digital beamforming as referred to antenna performances, but also to global performances (throughput allowed for communication system, etc..).

2.5 Beamforming based on Microwave Photonics

Due to the severe propagation conditions for millimetre-wave band signals, it is very important to have a fast and reliable radio resource management to ensure always the best possible performance of the wireless access networks.

In the electrical domain, the phase wave-plane on the antenna elements corresponding to the desired beam can be generated in two ways: at base-band using signal processing (with problems at high bit rate) or at RF using a passive network or phase shifters (in broadband systems we need a broad bandwidth and turn up a phenomena called beam squint). Therefore, with these beam-formers we are limited to narrow instantaneous bandwidth. For large aperture systems with a quite large number of elements, electrical beam-forming networks are unpractical in terms of size, loss and weight.

Optically beam-formed antennas benefit from the features of the optical fibre technology (low loss, size and weight) allowing distributed control of BS from a CS which is particularly critical in the case of access networks operating at the millimetre-wave (mm-wave) frequency bands.

Optical control techniques at the BS antennas can provide benefits in all the above areas and besides allowing true time delay capability necessary for squint-free wide instantaneous bandwidth array steering. Furthermore, fast switching and shaping capabilities may be achieved. Table 1 shows a comparison of electrically and optically beam-formed antennas.

Electrical beam-forming	Optical beam-forming
1. The optimum beam pattern is achieved by means of signal processing or RF/IF processing which is a limitation for high frequency and high bit rate systems. 2. High size and weight. Impractical for systems with large number of small cells. 3. Limited switching speeds: in the range of ms to μs. 4. Limited bandwidth	1. Adaptive beam-forming: no signal processing is required for beam-forming or beam-shaping as it is done in the optical domain. 2. Low loss and weight due to the use of optical fibre technology. 3. Fast switching capabilities: in the ns range. 4. TTD is easily achievable

Table 2-1.- Electrical and Optical beam-forming comparison.

There are several optical beamforming architectures based in different techniques. They can be divided in two main groups: these based on phase-shifting and these based on delaying the signal to each antenna element. Effectively, the beamforming can be achieved adjusting the phase of the signal at each antenna element. This can be achieved, for instance, using optical Butler Matrices composed by interconnected optical couplers that distribute the signal to all the antenna elements with a specific phase pattern. This technique, and generally all that are based on phase shifting have the common problem of beam squint resulting in narrow band architectures.

Wideband beamforming architectures can be realised introducing time delays among signals impinging the antenna elements, being commonly named TTD architectures. Using photonic techniques, these delays can be achieved either using delay lines that introduce an absolute delay among the signals or introducing differential delays by means of chromatic dispersion. Several architectures based on using different simultaneous optical wavelengths (i.e. WDM) with optical delay lines that introduce relative delays among the different wavelengths have been proposed. An optical wavelength-to-array element correspondence is generally established, so we only need to separate each wavelength toward its corresponding antenna. Usually, these wavelength-dependent delay lines are based on dispersive devices (a fixed length of highly dispersive or standard single-mode fibre or chirped fibre grating) but some other options are feasible as the use of different unchirped fibre gratings written on a single fibre.

Finally, the drawbacks that the optical beamforming present are the maturity of the photonic technology. Although an intensive research has been carried out in the development and integration of several photonic devices working together in a system, this technology seems not enough mature to supply competitive costs and mass production. Then, the optical beamforming architectures must be implemented nowadays by using discrete photonic devices, being its final price high.

Additionally, some optical beamforming architectures by using free-space optics have been proposed. These architectures exhibit a high potential in parallel processing, being possible to control several antenna elements with the same subsystem by introducing several delays and/or phase shifts simultaneously. However, these kinds of architectures are in an early stage and have problems as size, mechanical stability or diffraction that this technology exhibits have not yet clearly solved.

2.6 Special issues on Modelling aspects

Modelling array antennas (including their beam-former) raises specific problems for at least 2 reasons:

- a phased array is composed of numerous individual units (if passive, and even more if active); most are analogue, but some may be digital or photonic; an accurate prediction of the radiating pattern depends on a good modelling of all the parallel paths, including their dispersions, the multiple reflections and leakage from a path to another, etc.

- the coupling between the radiating elements, as numerous and close one to others, is known from a long time as a critical issue. Presently 2 kinds of methods are implemented (by ACE partners as others), neither of which solves totally the problem:
  - *"infinite array approximation"* assumes that the "embedded pattern" and the "active impedance" for an element surrounded by others, are identical all over the array: this is not true, even for large arrays especially when approaching its edges
  - *"element by element" computation* may be more precisely the coupling coefficient of each element with the others; but it becomes impracticable as soon as the number of elements increases significantly.

To compute accurately an array antenna overall performances (typically EIRP and radiated intermodulation products in transmit; G/T in receive, related also to Signal to Noise Ratio), methods for modelling full active arrays need to be set-up, taking into account especially the 2 problems presented here-above.

This has been the topic of the WP 2.4-2. Its main present results are summarised here-after, from the abstract of Deliverable A2.4-D3:

1. By chaining so-called S-parameter blocks using the ADS tool, it was found that the RF layer of active antenna systems could be analyzed, although solutions for problems not usually managed in ADS *e.g.* the free-space to guided-wave interface, had to be developed. Simulations of a 4x4 array with antenna elements, active modules and RF distribution network has been successfully built (D3-§2)..

2. By creating a "system-transfer function type" in Matlab/Simulink it has been shown that the properties of signals and noise can be analyzed further down, *i.e.* into the DBF layer of an antenna system. (D3-§3).

Both frameworks 1 & 2 have been adapted for computing the array-antenna radiating pattern, which is not implemented within the commercial version of ADS nor Matlab/Simulink, as these tools are initially "circuit-orinted".

3. In order to go ahead about the effects of mutual coupling between the antenna elements, a test-case has been defined and submitted to various partners for checking the methods they have experimented for such modelling (D3-§4). Measurements of all coupling coefficients have been performed on the test-case to validate the best tools results.

This summary shows clearly that there is still a lot of work to do until reaching modelling tools of full arrays, having especially solved the 2 problems described at the beginning of this §2.6. Such effort will be pursued with the ACE-2 contract.

2.7 Special issues on conformal arrays aspects

Like in the planar case the most important parameter when analysing conformal arrays is the mutual coupling which affects most of the antenna characteristics. Due to the curved surface, mutual coupling between the elements of a conformal array is significantly different than for the planar array. Therefore when designing conformal array antennas it's not possible to use programs for designing planar arrays.

Second parameter that should be mentioned is the maximum gain of the observed conformal array. According to the theorem by A. Hessel and J.C. Sureau which states : "The maximum realised gain of an array in a specified direction is equal to the sum of the individual element gain function values in the direction of interest. The appropriate excitation is such that the amplitudes are proportional to the respective element patterns in the direction of interest and the phases yield total phase correction for each element." As a consequence, an area of active elements has to be defined for every specific direction of the main beam because antenna elements which point in directions very different from the direction of the main beam have no practical influence since their optimum excitations are very low. Furthermore, the optimum excitation amplitude and phase of each array element depend on the direction of the main beam, i.e. with steering the main beam the optimum excitations change as well.

The third parameter is the polarisation, which is usually very well defined in planar cases. However, in conformal case polarisation can significantly vary over the radiation pattern, and therefore polarisation control is a very important parameter which has to be taken into account in conformal array design.

One more parameter which is specific for conformal arrays is the side lobe level. As it can be expected in principal conformal arrays have larger side lobes then the equivalent planar arrays.

3 SYNTHETIC MAPPING OF EUROPEAN ON GOING RESEACH

"Geographical maps" of on-going research in various laboratories and companies are presented on the following pages:

- they first present part of the quite large basis on which was set-up the syntheses presented in Deliverable D4, and summed-up here-above in §2;
- they also show the complementary distribution over Europe, among big companies, public research institutes, and universities;
- finally, they can help to identify potential future collaborations (for instance, for building STREPs or FETs in answer to E.C. calls in relevant domains).

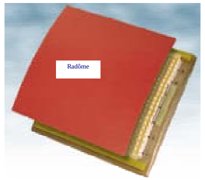
These maps are based on the answers received from the questionnaires about array antennas, sent to all the A2.4 partners in 2004.

3.1 Reflectarrays

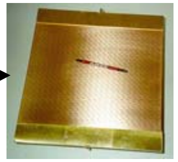
3.2 Passive Feeding/Combining Networks

Univ. Of Birmingham:
- Corporate Patch Arrays
- Multibeam Patch Arrays
- Seq. Rotated Patch Arrays

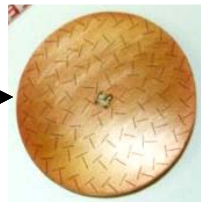
Thalès:
- Alabama



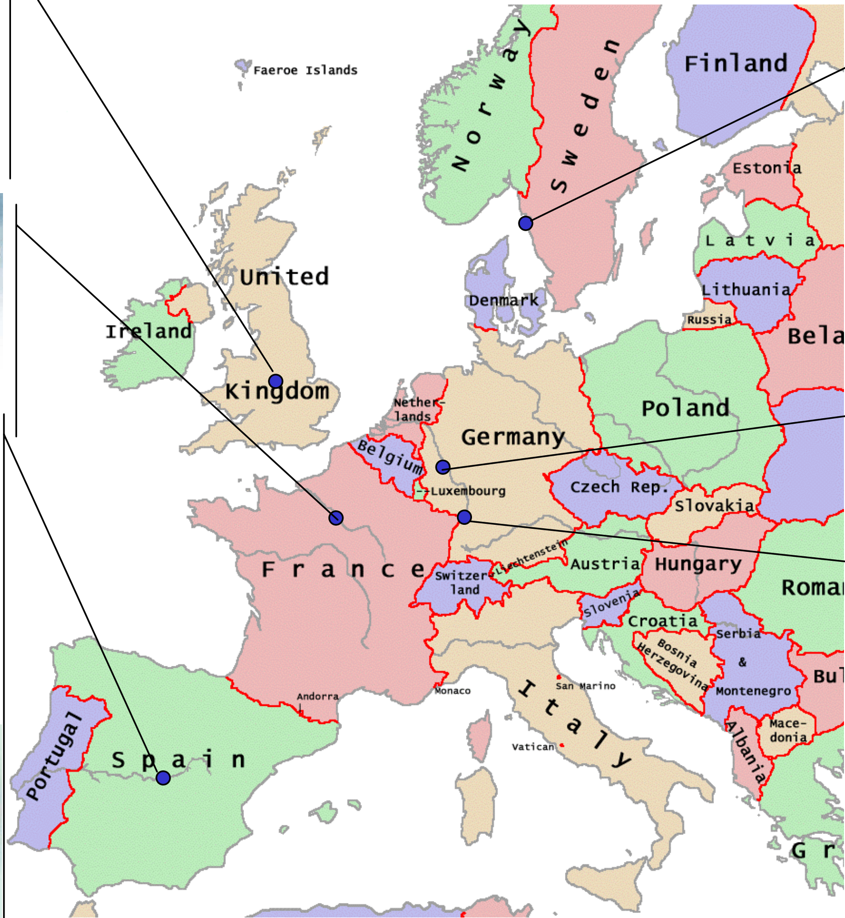
UPM
- Block Elements for base-station
- MoMIA →



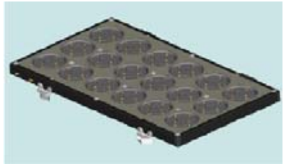
- TaCoA
- RaLiSA →



- LPRAA



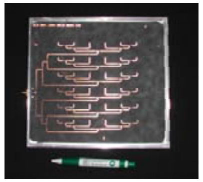
SAAB E.S.
- Remote Sensing
- GPS Occultation



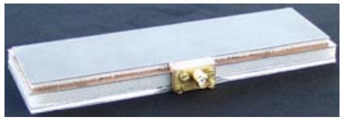
- Dual Pol SAR

DLR
- NRN
- E-SAR

UKARL
- TerraSAR-X



- ARDS



3.3 Analogue Controllable Beamforming Networks

Ericsson Microwave Systems:

•ERIEYE

•ARTHUR

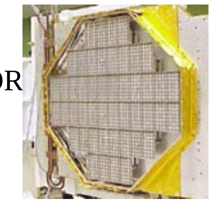
•GIRAFFE AMB

Univ. Of Birmingham:
•Active Integrated Array

Ku Leuven
•Satellite Rx terminal

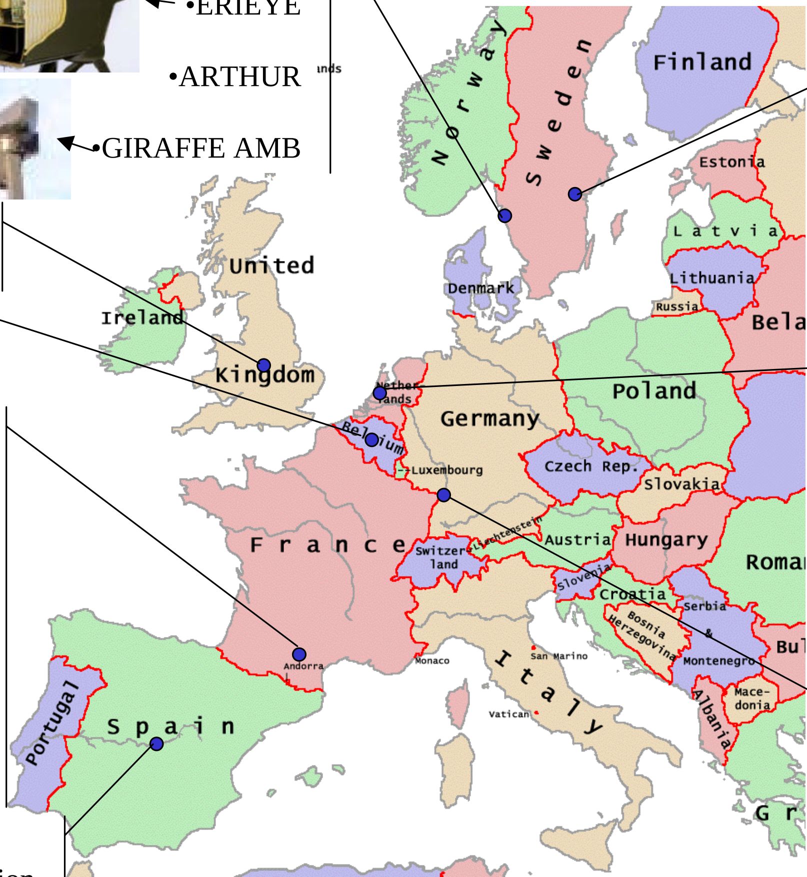
ALCATEL:

•Conical Conformal Array

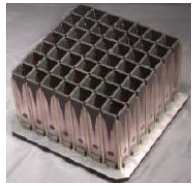


•STENTOR

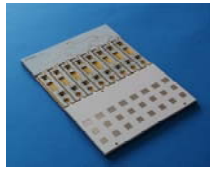
UPM
•Block element for base station



FOI:
•TSA

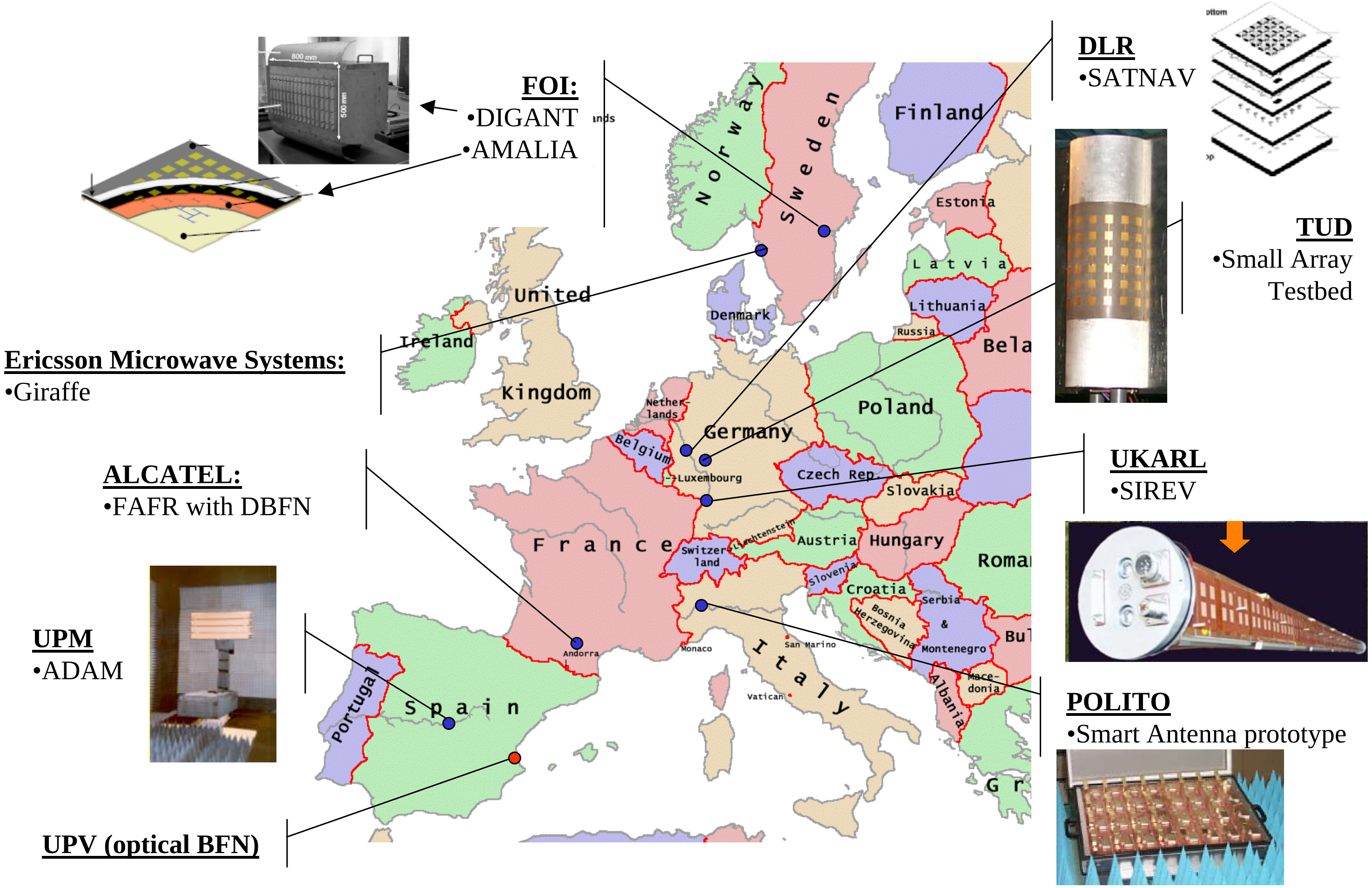


TNO
•APAR
•MiniSAR



UKARL
•Inmarsat-Ant

3.4 Digital Controllable/Adaptive Beamforming, and Optical Beamforming Networks



4 CONCLUSION

4.1 Why beam-forming?

Beamforming is the basis of any antenna array

- in its simplest form, it combines passively several low-gain elements (patches, dipoles, slots…), to obtain a large medium or high gain array-antenna, mostly flat, so more compact than a reflector antenna.
- As a further step, it may enhance antenna performances by introducing when required some reconfigurability.
- At the highest level, it can also be coupled with signal processing: the antenna is then as "a sampled aperture", with multiple signal-observation points (speaking for a receive one), which may be combined in various ways.

***** As the most usual option, an **array antenna coupled to a controllable beamforming network** allows:

- ❑ Improving antenna array gain: thanks to beam-forming, signals coming from the direction of interest are coherently summed, therefore improving the C/N ratio.

- ❑ By forming multiple beams (even fixed with a specific passive network) and switch on the desired beam, one can cover multiple direction with a maximum gain with a single fixed aperture antenna

- ❑ Better controlling the radiating pattern : the use of a sampled aperture leads to a better control of aperture illumination then bring a better shaping of the radiating pattern, with low sidelobes, and if required nulls in possible interference directions.

- ❑ Providing multiple beams with a single physical aperture.

  - ➢ By using multiple simultaneous beam coverage, an important antenna gain can be provided on a wide coverage with a single aperture, which is not possible with a single beam due to physical relation between beamwidth and maximum gain.

  - ➢ By using spatial filtering provided by multiple beams, some resource re-use (frequency, time slot, code) can be introduced. This leads to spectrum efficiency enhancement and communication systems capacity improvement. The best known applications are frequency reuse techniques (e.g. for satellite antennas), or SDMA techniques (base-station antennas)

***** In addition of these advantages brought by all array antennas, the array antenna can be **coupled to a reconfigurable beamforming networks**, thus introducing a great flexibility in beam-forming capacity. It allows to adapt the antenna to particular conditions, keeping a single fixed physical aperture.

- ❑ Beam pointing :

  The beam of the antenna can be used to track a target (radar case). A mobile user antenna can also track base-station to guaranty the best link all over the communication. More generally, the beam can be reconfigured so as to guaranty the best possible beam configuration in a given situation between a user the base-station avoiding –partially, or fully- mechanical control of the antenna position.
  Beam pointing modification can also be used in order to bring capacity in a particular direction, thus leading to a better resource management, and better exploitation of available spectrum.

- ❑ Beam shaping

  Beam shaping can be modified in order to cancel new appearing interferers – thus guarantying a better co-channel interference reduction for communication systems, or a better detection of targets for radar application.

***** The third logical step in improving antenna performance is to provide **adaptive array antennas**, that is antenna that are able to adapt themselves, by appropriate processing, their antenna pattern in order to have the best possible compliance to environment. Two aspects can be distinguished in this area :

- Use of the antenna as a sampled aperture : When considering array antenna, one can consider the possibility to use all spatial sample for further analysis of direction of arrival, number of users, position of targets. In this case array antenna signals are used as information for spatial processing,
  - either to analyse external conditions : determine directions of arrival of users or jammers for example
  - or to improve antenna performances by modifying the beamforming coefficients so as to take into account antenna imperfections : coupling between radiating elements, pointing errors, variation in the structure of the antenna…

- Use of full adaptive processing : the antenna can be designed so as to guaranty itself appropriate beam-pointing, in order to follow a target, cancel moving interferers…

***** The last step consists in **coupling antenna spatial filtering with time processing**. In this last stage of evolution the antenna functionality is not separated any more from other communication or radar system functionalities. Much opportunities are raised by such space-time processing. Among them, but not exhaustively, can be distinguished :

- The possibility to introduce adaptive space-time processing, with for examples
  - Reduction of delay spread and multipath fading for a mobile communication system
  - Space-time processing for radar application : Direction of arrival of the target is not determined in a separate processing but within a processing analysing the position and the speed of the target

- The possibility to use jointly adaptive spatial filtering and smart resource management. For communications systems, this means the possibility to bring capacity where required by moving beams and allocating frequency resource where and when required.

4.2 Beamforming methods as applied to various applications

In present and foreseen applications, appear more and more demands for better flexibility, thus tending to go towards controllable antennas.

The specifications of systems also tend to be more and more stringent in terms of number of beams, precision in beamforming, bandwidth.

On the other hand, more mature technologies are dealing with previous (or present) generation beamforming antennas, that is to say, fixed beamforming antennas, or reconfigurable antennas with a small number of beams, moderate bandwidth, etc…It results that considering the suitability of a beamforming technique to a specific mission mostly results in a trade off between the required flexibility, the performances in terms of bandwidth, number of beams, … and the maturity of the technique, so finally the cost of the antenna.

Following tables present a set of well suited solutions for each mission category (each of the five main application types presented in Deliverable D1). Blank blocks correspond to seldom used solution, but not totally forbidden.

We split it in 2 different tables, depending on the considered term:

- The 1st table considers present requirements, corresponding to short term applications.
- The 2nd table addresses more challenging missions, on-going studies, and future applications

An Excel table with appropriate graphical exploitation has been built to help identifying what are the advantages and drawbacks of each beamforming technique; it is presented in Annex (§ 5). The results have been cross-checked with the personal experience of WP members; for building the 2 following tables.

4.2.1 *Present Applications Requirements*

Techniques \ Applications		Base-station antennas: Passive	Base-station antennas: Adaptive	Commercial and civil Radar application	Spaceborne array Antennas	Defence Radar applications	User terminal Array
Reflectarrays	Passive			☺	☺		☺
Reflectarrays	Active						
Passive Feeding/Combining Network	Single Beam	☺	☺	☺	☺	☺	☺
Passive Feeding/Combining Network	Multiple Beams		☺	☺	☺	Δ/Σ pattern in receive	
Analogue Controllable Beamforming Networks				☺	☺	☺	
Digital Controllable /Adaptive Beamforming						☺	
Beamforming Based on Microwave Photonics							

Table 4-1 : Suitability of various BF techniques to various applications / Present Requirements.

4.2.2 Future Applications Requirements

Techniques \ Applications		Base-station antennas		Commercial and civil Radar application	Spaceborne array Antennas	Defence Radar applications	User terminal Array
		Passive	Adaptive				
Reflectarrays	Passive	☺			☺		☺
	Active		☺	☺	☺	☺	
Passive Feeding/Combining Network	Single Beam					(still candidate in transmit)	
	Multiple Beams	☺	☺				☺
Analogue Controllable Beamforming Networks				☺	☺	☺	☺
Digital Controllable /Adaptive Beamforming			☺	☺	☺	☺	☺
Beamforming Based on Microwave Photonics			☺		☺	☺	

Table 4-2 : Suitability of various BF techniques to various applications / Future Requirements.

As a general conclusion, it can be pointed out that passive solution are mostly used for present applications, except for “high-tech” (but not low-cost) defense radar : this is mostly due to the lack of full maturity of active, digital, and photonic based solution.

For future missions, it is foreseen that more flexible solutions will be required, which explains the great interest on active reconfigurable solutions. However, this solutions still suffers from lack of maturity, or from a too high cost, and some bottlenecks are still remaining, in particular when a large bandwidth is required. Thess aspects are major topics for futur researches.

5 ANNEX : HELP TOOL FOR TRADE OFF'S AMONG BEAM-FORMING METHODS

In the frame of ACE activities, it has been proposed to build a systematic trade off technique, providing a help to assess advantages and drawbacks of each beamforming techniques as applied to a given application. In this aim, information collected by mean of questionnaires, and analysis provided by each sub-group leaders, as well as information collected concerning specific requirements of each type of mission serve as a database.

This information are presented more in details in D4, we here only give main guidelines to use the tool that has been developed, and also give the table that are the results of previous analysis concerning missions needs and beamforming techniques performances

5.1 General considerations

The main difficulty in comparing various beamforming methods as applied to various type of application is that a global performance, taking into account various non-homogeneous criteria must be assessed. Criteria to be involved can be either quantitative (number of beams, mass, consumption) or qualitative (requirement for flexibility, maturity…)

Furthermore, the importance of various requirements is not the same, so that various performances should be "weighted" in order to have the best possible assessment of technique fitting to various missions.

Finally the method proposed to assess beamforming techniques fitting to various missions was as follows :

1. We defined a set of elementary criteria. This list could be completed by any "user" of this method if necessary. Furthermore, it is possible to "cancel" one of the criterion of it not applicable to a particular mission. A common scale is proposed to mark various requirements (see §5.3.1).
2. We defined an arithmetic criterion, combining weighted performances of each beamforming technique, taking into account the importance of various requirements. The maximum quotation is given each time the performance is equal or exceed the requirement.
3. All beamforming techniques and typical applications have been quoted by partners and sub-groups responsibles. This quotation was used as a reference to assess the general performances of beamforming technique within the frame of this work package. However, the possibility to define a particular mission or the performances of a specific beamforming method is kept for the user. The present work will in this particular case serve as a database.

5.2 Set of elementary criteria

This list (detailed in previous Deliverable D4) can be completed by the user if necessary, to take into account specific needs or characteristics.

- Mission related criteria
  - Fast beam scanning or forming
  - Multibeam capacity
  - Absolute and relative bandwidth
  - Multiband capacity

- Performance Criteria
  - Accurate Beamforming Capacity (requirement for annex functions, like calibration..)
  - Loss limitations in beamforming process
  - Power handling
  - PIM

- Requirements related to implementation
  - Ease of building, cost constraints
  - Mass and volume constraints
  - DC consumption and thermal control constraints
  - Level of Maturity

5.3 Quotation of requirements and performances

5.3.1 General rules

In order to provide a consistent comparison between techniques, and assess as well as possible fitting of various beam-forming techniques to different applications, we should quantify more precisely the criteria previously listed.

For each application, we had to assess the requirements “range”, by defining some “difficulty scale” applicable to each criterion.

For all requirements range and performance assessment, we chose to work with the same scale ranking from 0 or 1 (depending on the criteria) to 5.

- For criteria mainly related to “requirements”, the highest rates correspond to the most difficult or most constraining requirement: high bandwidth, high need for flexibility but also low losses, low cost.
- For criteria related to “performance”, highest rates correspond to “best” performances : high bandwidth, good flexibility, low RF- loss or low cost.

In following §5.3.2, we propose rates for the various criteria listed in §5.2 above

5.3.2 Quotation scales

Following figures describe the different scales that have been used in the frame of the present work :

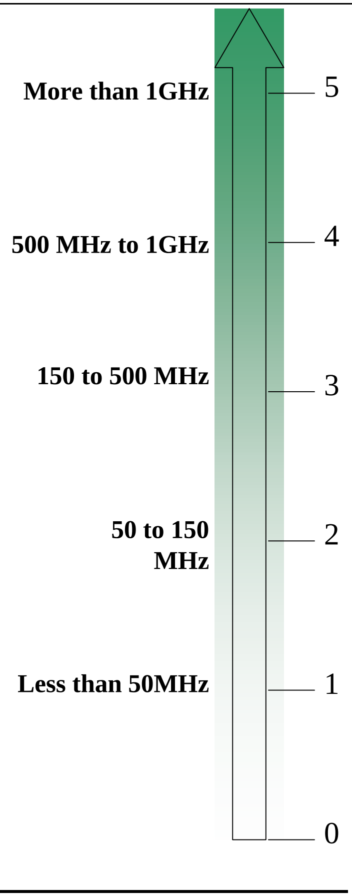
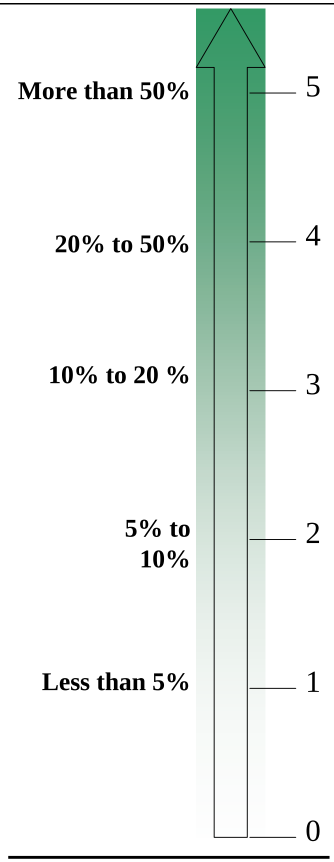
A- MISSION RELATED CRITERIA

Reconfigurability, Fast Beam Changing

5	**Fast and Full reconfigurability** Exple : Tracking radar including antijaming with adaptive processing
4	**Reconfigurability at moderate rate** Exple : Slowly moving terminal antenna pointing towards base station or satellite
3	**Reconfigurability at initialisation level** Exple : User terminal to be pointed towards localised base station. Each time terminal is initialised.
2	
1	**Reconfigurability for mission redefinition** Exple :For a satellite antenna, change in orbital position, or demand for communication in new countries requires change in beam shape. Few changes in a lifetime
0	**Fixed Beams**

Multibeam Capacity

5	**More than 64 beams** Very highly demanding telecommunications missions
4	**Up to 64 beams** Exple : Highly demanding telecommunications missions
3	**Up to 8 beams** Exple : multibeam automotive radar or advanced base-station
2	**3 /4 beams** Exple : Monopulse application or short term base-station
1	**Single Beam**
0	

<table>
<tr><th>Instantaneous absolute bandwidth</th><th>Relative Bandwidth</th></tr>
<tr><td>
</td><td>

NB : relative % is $\Delta f/f_c$, f_c being the central frequency and Δf the absolute bandwidth.</td></tr>
</table>

B- PERFORMANCE RELATED CRITERIA

Scale	Accurate Beamforming Capacity	Loss impacting Link Budget
5	**High Needs/performance in beam pointing and shaping/calibration precision** Exple : Highly directive antennas providing narrow beams, antennas with anti-jamming system requiring high rejection	**High Needs/performance in loss limitation**
4		
3	**Moderate Needs/performance in beam pointing and shaping /calibration precision** Exple : Directive antennas with required pointing precision due to edge of coverage losses, and isolation requirements related to interference between beams	**Moderate Needs/Performances in loss limitation**
2		
1	**Low Needs/Performances in beam pointing and shaping/calibration precision** Exple : Non directive Antennas (very wide beamwidth), no drastic constraints on antenna pointing nor on sidelobe level or jammer rejection	**Low Needs/Poor Performances in loss limitation** Exple : Not critical Link budget
0		

C- HARDWARE IMPLEMENTATION CRITERIA

Mass and Volume	Scale	DC Consumption/Thermal Control	Scale
Hard constraint on mass and volume/ Compact/light antennas Exple : Constraint on spatial antennas, constraints on mobile phone antennas.	5	**High need for reduced consumption Hard constraints on thermal dissipation** Exple : Constraint on thermal dissipation related to high antenna integration and difficulty to dissipate. Constraints on reduced consumption (mobile phones, space antennas)	5
	4		4
Moderate mass and volume Exple :transportable user station	3		3
	2		2
Low constraints on mass and volume/Big size/Heavy antennas Exple :Fixed base station antennas (gateways)	1	**Low need for reduced consumption No constraints on thermal dissipation** Exple : Antennas for base station where DC power is quite cheap,radiatemoderate power, and may dissipate rather easily. Big antennas with important surface to be used for thermal dissipation purpose.	1
	0		0

Easy to build/Low cost		Level of Maturity	
Low cost/ reproducible antennas Exple :Low cost antenna for mobile phones to be produced in great quantities and sold to a very wide market, cost reduction being a commercial stringent condition.	5	**Actual system proven** System completed, qualified, already proven in operational environment	5
Moderate cost antennas Exple :Antennas for specialised though still wide market	4	**System or subsystem demonstrated** In an operational or relevant environment	4
Moderate to expensive cost antennas Exple :Reproducible antenna for reduced production : base-station	3	**Component or breadboard validation available** In relevant or laboratory environment	3
High cost antennas Exple :Space antennas with rather high cost (little recurrence) but still submitted to commercial competition	2	**Proof of concept available for critical functions**	2
Single produced antennas Exple : Antennas for specific scientific applications or earth observation from space	1	**Basic principle reported, technology concept formulated** Concept on study	1
	0		0

5.4 Synthetic rating of the various criteria for each application

In the 1st following table, those who where responsible for the "state-of-the-art" review performed in 2004 for each array antenna application domain, rated the requirements for the various applications, according to the "difficulty scales" defined in §4.2 (from 0 to 5).

After a "first-run" ranking, it appeared that should be added to the marks of this 1st table some "relative weighs" or "mandatory coefficient" (from 0 to 10), in the following sense: when the requirement is present, is it very compulsory or not ? this is presented in the 2nd table for each application.

Here is an example showing more concretely how the 2 marks will be combined (from the 2 tables) within on overall tool under constaruction:

- if a high number of beams is preferred for the concerned application, but this number may be decreased in order to reduce the antenna cost, a high level mark will be given for the multibeam criterion, but this constraint is relaxed by giving a reduced weight to this need.
- on the contrary, for a monopulse antenna where three beams are absolutely necessary, the absolute rating is low, but the weight given to this need is high.

For the weight range, it has been proposed to give a default value of 5 to all weights, and to increase this weight value up to 10, for the case where the concerned requirement is very compulsory. A "1" mark means that the concerned need is present, but can be rather easily relaxed.

A weight 0 can be associated to a given criterion if no specification is given or if the criterion is not applicable

All these figures are of course average values, because within the same kind of application, requirements can vary from one particular mission to the other. These table must then be understood as a database for "typical" application requirements

.

		Base-station antennas	Commercial and civil Radar application	Spaceborne array Antennas	Defence Radar applications	User terminal Array
Mission related criteria	Fast Beam Change	1 in passive antennas 5 (adaptive antennas)	**0** most applications **4** automotive	2: slow beam-scanning in low orbit; few beam-reshaping in GEO, except rare beam-hopping	5 (fast beam scanning very important)	5 mobile applications 4 stationary users
	Multibeam Capacity	2 in passive antennas 3 (adaptive antennas)	**1** most applications **3** automotive & ATC	3: growing requiremt, but still minoritary, especially for very numerous beams	2 (monopulse) 5 (future systems)	2 one or two beams at same time
	Wideband	3 (instantaneous Bw) 4 (relative Bw, the antenna should cover several bands)	**2** most applications **4** Remote Sensing, & Ind. Sensors	Absolute: 4 Relative: 3	3 (instantaneous) 4 (usable band)	4 Instantaneous bandwidth, high data rates needed
	Multiband	4 (the antenna should cover several bands)	**0** most applications	1: mostly Tx/Rx for telecom; dual-band sometimes for Obs-Science	2	1 separate bands for transmit and receive
Performance criteria	Accurate Beamforming Capacity	1 in passive antennas 4 (adaptive antennas)	**2** most applications **4** Automotive & ATC	4: very important, especially for telecom	5 (low sidelobes and adaptive beamforming)	5 high directivity, nulling, SLL reduction
	Loss impacting link budget	2 (is not critical)	**3** most applications	5: link budget is always very stringent	3 (4 for long range applications)	5 mainly for Ka-band: critical link budgets
Hardware implementation criteria	Easy to build/low cost	3(the cheapest is the best, less critical for adaptive antennas)	**5** most applications **2** ATC & Remote Sensing	2: harsh environment + very high reliability= high cost, but pushed down by competition	3	2 -5 from professional terminals to small user terminal
	Mass and volume	1 (is not critical)	**3** most applications **1** ATC	4: any added Kg is costly, room restricted	5 for air systems 3 for ship and ground systems	2-4 from professional terminals to small user terminal
	DC consumption / thermal control	1	**3** most applications	4: any added Watt is costly/ thermal control difficult due to: vacuum + sun- shine	4 for air systems 2 for ship and ground systems	2-4 from professional terminals to small user terminal
	Level of Maturity	5 (passive antennas) 4 (adaptive antennas)	**5** most applications		5	3-5 e.g. DBF terminals in Ka-band still under development

Table 5-1 : Rating the various application requirements, according to the “difficulty scales” defined in §5.3.2 (0 to 5 marks)

		Base-station antennas	Commercial and civil Radar application	Spaceborne array Antennas	Defense Radar applications	User terminal Array
Mission related criteria	Fast Beam Change	1 (passive antennas) 9 (adaptive antennas)	7	2: presently, seldom reconfigurability is required	7 (fast beam scanning very important)	10 (mobile applications)
	Multibeam Capacity	2 (passive antennas) 9 (adaptive antennas)	6	8: when required, compulsory	10 (monopulse) 7 (future systems)	5 (typ. one beam needed)
	Wideband/	3 (single band antennas are also used)	8	10: perfos on used BW are compulsory	5 (instantaneous) 9 (usable band)	10 high data rates is major criterion (absolute bandwidth)
	Multiband	3 (single band antennas are also used)	2	10: when required, compulsory	2	5 mainly separate tx and rx band
Performance criteria	Accurate Beamforming Capacity	5	4	10: Sat antennas specs always mandatory	7 (low sidelobes and adaptive beamforming)	10 (mobile applications)
	Loss impacting link budget	5	5	10 Sat antennas specs always mandatory	5 (9 for long range applications)	10 e.g. for Ka-band mobile satellite communications
Hardware implementation criteria	Easy to build/low cost	5	10	4 the cheapest is the best, but not so low	3	10 for small portable user terminals 5 for professional terminals, (on airplanes)
	Mass and volume	5	8	8: Few NCs vs specs may be negociated	8 for air systems 3 for ship and ground systems	10 for small portable user terminals 5 for professional terminals, (on airplanes)
	DC consumption / thermal control	5	5	8: Few NCs vs specs may be negociated	8 for air systems 3 for ship and ground systems	10 for small portable user terminals 5 for professional terminals, (on airplanes)
	Level of Maturity	5	0		5	10 (important for mass market and professional users on airplanes)

Table 5-2 : :"Relative weights" or "mandatory coefficients" (0 to 10) for application requirements (when they apply, are they very compulsory or not?)

5.5 Rating performances of various beamforming techniques

Following tables give average values for performances characterisation of various beamforming techniques, versus the same criteria (requirements, performances), used for rating versus applications in previous §5.4.

These quotations represent mean values, because within the same kind beamforming network, performances can vary from one particular case to the other. These table must then be understood as database.

		REFLECTARRAYS		
		Passive	Active	
			With diodes	With MEMS
Mission related criteria	Fast Beam Changing	0	5	4
	Multibeam Capacity	2 (fixed beams)	2	2
	Wideband	3 (relative Bw is more significant)	3	3
	Multiband	3	1	1
Performance criteria	Accurate Beamforming Capacity	4	3	3
	Loss impacting link budget	4	1	3
Hardware implementation criteria	Easy to build/low cost	4	3	3
	Mass and volume	3	2	2
	DC consumption/thermal control	5 (no DC consumption)	3	4
	Level of Maturity	6	4	4

Table 5-3 : Reflectarrays performances

		PASSIVE Feeding/Combining Network		
		Waveguide network	Microstrip / stripline network	
			Conventional	Suspended
Mission related criteria	Fast Beam Change	0	0	0
	Multibeam Capacity	0 for combining network. 3 (Butler Matrices)	0 for combining network	0 for combining network
	Wideband/Multi band	1	2 - 4	2 - 4
Performance criteria	Accurate Beamforming Capacity	5	4	4
	Loss impacting link budget	5	1	3
Hardware implementation criteria	Easy to build/low cost	1 - 3	3 - 5	1 - 2
	Mass and volume	1 - 3	3 - 5	3 - 5
	DC consumption/th ermal control	0	0	0

Table 5-4 : Passive Feeding/Combining networks performances

		ANALOGUE CONTROLLABLE BEAM-FORMING NETWORKSS		
		PASSIVE (CENTRALISED AMPLIFICATION)	ACTIVE (AMPLIFIERS BETWEEN R.E.[2]. & CONTOLLABLE DEVICES)	
			IN RECEIVE (RX)	IN TRANSMIT (TX)
Mission related criteria	Fast Beam Scan / Forming	4	5	5
	Multibeam Capacity	2	4	4
	Wideband	3	4[3]	4
	Multiband	1	2	2
Performance criteria	Accurate Beamforming Capacity	3	4	4
	Loss impacting the link budget	1	5	5
Hardware implementation criteria	Easy to build/ low cost	3	2	1
	Mass and volume	3	2	1
	DC consumption/ thermal control	3	2	1
	Level of Maturity	5	4	3

Table 5-5 : Analogue controllable beamforming networks performances

[2] R.E ; : Radiating Element

[3] Wideband capability needs to add True-Time Delay control (at least at subarrays level), in case of wide scanning & large array size vs λ

		Digital Controlable/Adaptive Beamforming	
		Moderated Bandwidth	Wideband digital beamforming
Mission related criteria	Fast Beam Change	5	5
	Multibeam Capacity	5	5
	Wideband	3 for absolute bandwidth (global bandwidth)	3 for absolute bandwidth (global bandwidth)
	Multiband	0	0
Performance criteria	Accurate Beamforming Capacity	5	5
	Loss impacting link budget	3	3
Hardware implementation criteria	Easy to build/low cost	3	1
	Mass and volume	3 when separated DBF processor can reach 5 (super-integrated antennas)	1
	DC consumption/thermal control	3	1
	Level of Maturity	5 for terrestrial radar antennas 3 for other systems	2

Table 5-6 : Digital Beamforming Network performances

		BEAM FORMING BASED ON MICROWAVE PHOTONICS
Mission related criteria	Fast Beam Scan / Forming	4
	Multibeam Capacity	3
	Wideband / Multiband	5
Performance criteria	Accurate Beamforming Capacity	5
	Loss impacting the link budget	4
Hardware implementation criteria	Easy to build/ low cost	1
	Mass and volume	2
	DC consumption/ thermal control	3

Table 5-7 : Beamforming based on Microwave Photonics performances

5.6 Exploitation example

These values are used as a reference to assess advantages and drawbacks of various techniques as applied to applications. The Excel table is available on the ACE-VCE and can also be used to assess a particular beamforming method, or a particular application. Following figures give example of a possible exploitation of this table, on a fictive mission.

5.6.1 Description of needs

Needs must be described following previously presented scales for each of the criterion. These values are entered in the excel table as presented in the next figure :

		Mission related criteria		
		Fast-beam Change (scanning/forming)	Multibeam Capacity	Wideband/Multiband
	REFERENCE (most requiring mission)	5	5	5
Base station antennas	Passive Base Station Antennas	1	3	4
	Adaptive Base Station Antennas	4	5	4
	Commercial and Civil Radar Application			
	Spaceborne Array Antennas	1	4	3
	Defense Radar Applications	5	4	3
	User Terminal Array			
	My mission	1	1	4

Quotation for requirement "Multibeam Capacity" in Spaceborne Array Antennas (Database)

• • • Others criteria

Quotation for requirement "Multibeam Capacity" in a given application (possibility to copy/paste one line of data base)

Figure 5-1 : description of needs for a particular mission

Following kind of graphical exploitation is proposed in order to compare the needs of the mission to standard mission described in the database.

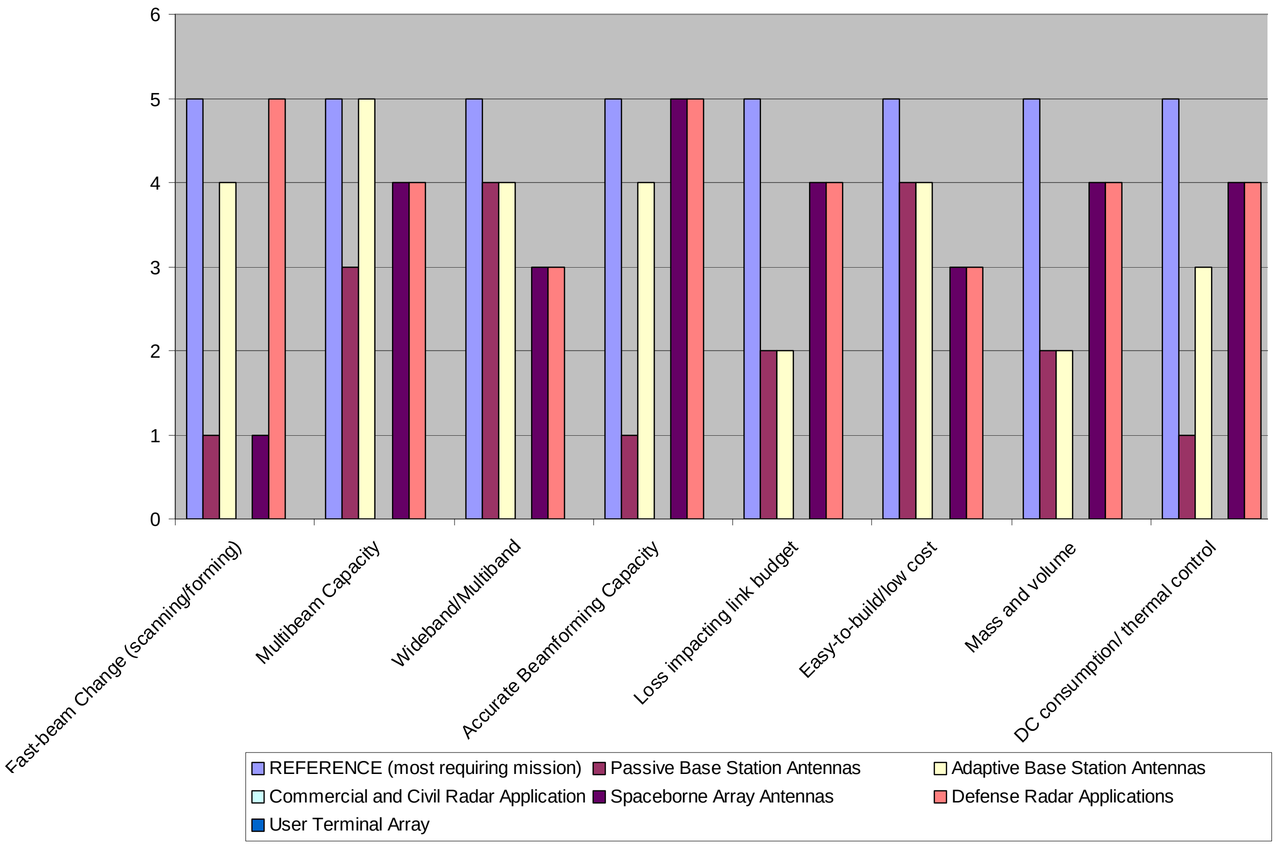


Figure 5-2 : Comparison of needs for various missions

5.6.2 Beamforming Method Quotation

Beamforming method “performances” and characteristics must be described following previously presented scales for each of the criterion. These values are entered in the excel table as presented in the next figure :

			Mission related criteria		
			Fast-beam Change (scanning/forming)	Multibeam Capacity	Wideband/Multiband
		REFERENCE (ideal antenna)	5	5	5
Reflectarrays		Passive Reflectarrays	1	4	3
	Active Reflectarrays	Active Reflectarrays with diodes	5	4	3
		Active Reflectarrays with MEMs	3	4	3
Passive Feeding/Combining Network		Waveguide Networks	3	3	2
	Microstrip/Stripline network	Conventional Microstrip/stripline network	3	3	4
		Suspended Microstrip/stripline network	3	3	4
Analogue Controlable Beamforming Networks		Passive Analogue Controllable BFN	4	2	3
	Active Analogue Controllable BFN (ampli. between R.E. and control. device)	Active Analogue Controllable BFN in Rx	5	5	3
		Active Analogue Controllable BFN in Tx	5	5	3
		Digital BFN	5	5	2
		BF based on Microwave Photonics	3	4	5
		My BFN	5	5	5
		My BFN2	1	1	1

Quotation for the criterion “Multibeam Capacity” for Waveguide networks (Database)

• • • Others criteria

Quotation for criterion “Multibeam Capacity” in a given realisation (possibility to copy/paste one line of data base)

Figure 5-3 : Comparison of various beamforming methods performances

Following kind of graphical exploitation is proposed in order to compare the performances of several beamforming methods, for each of the criterion, in order to identify what could be the advantages and drawbacks of the considered beamforming network.

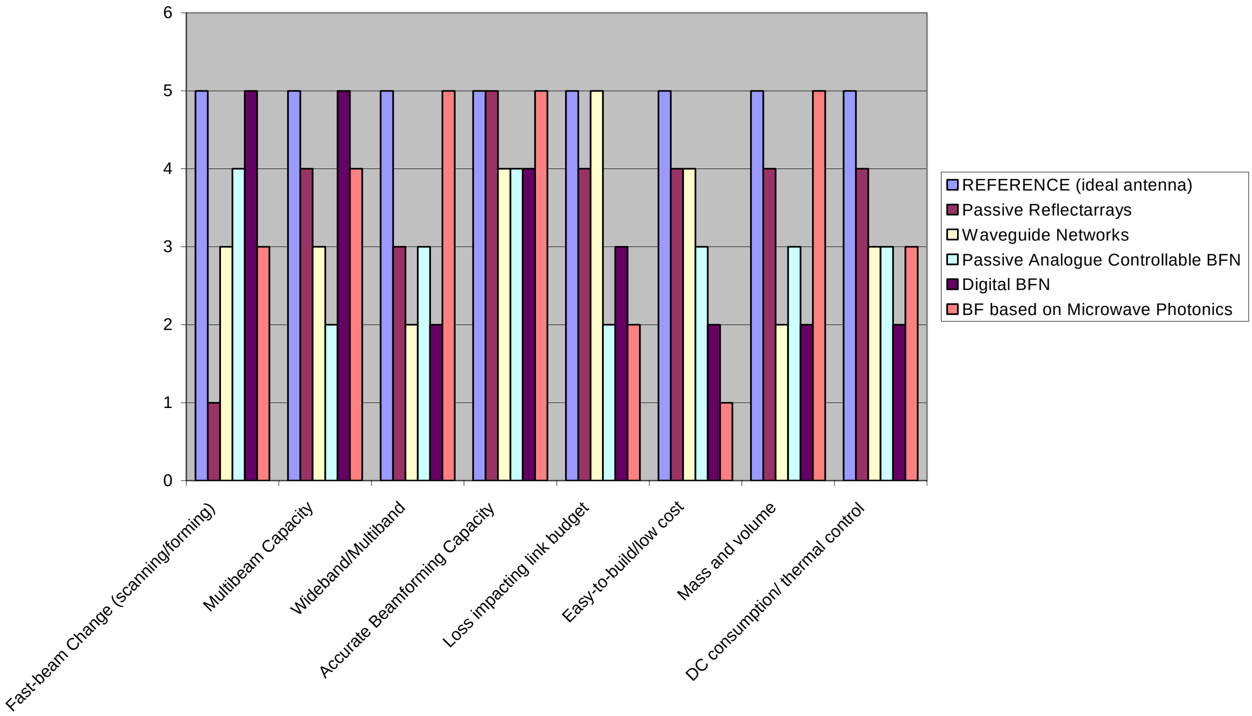


Figure 5-4 : Comparison of perfromances for various beamforming techniques

5.6.3 *Assessment of beamforming method suitability*

Normalised weighted quotation, assessing the suitability of beamforming method for one of the requirements of the specific mission is then computed. The sum of partial quotation gives a global mark.

These marks allow to compare the performances of the beamforming method as applied to the specific mission, giving rise to following type of graphical exploitation :

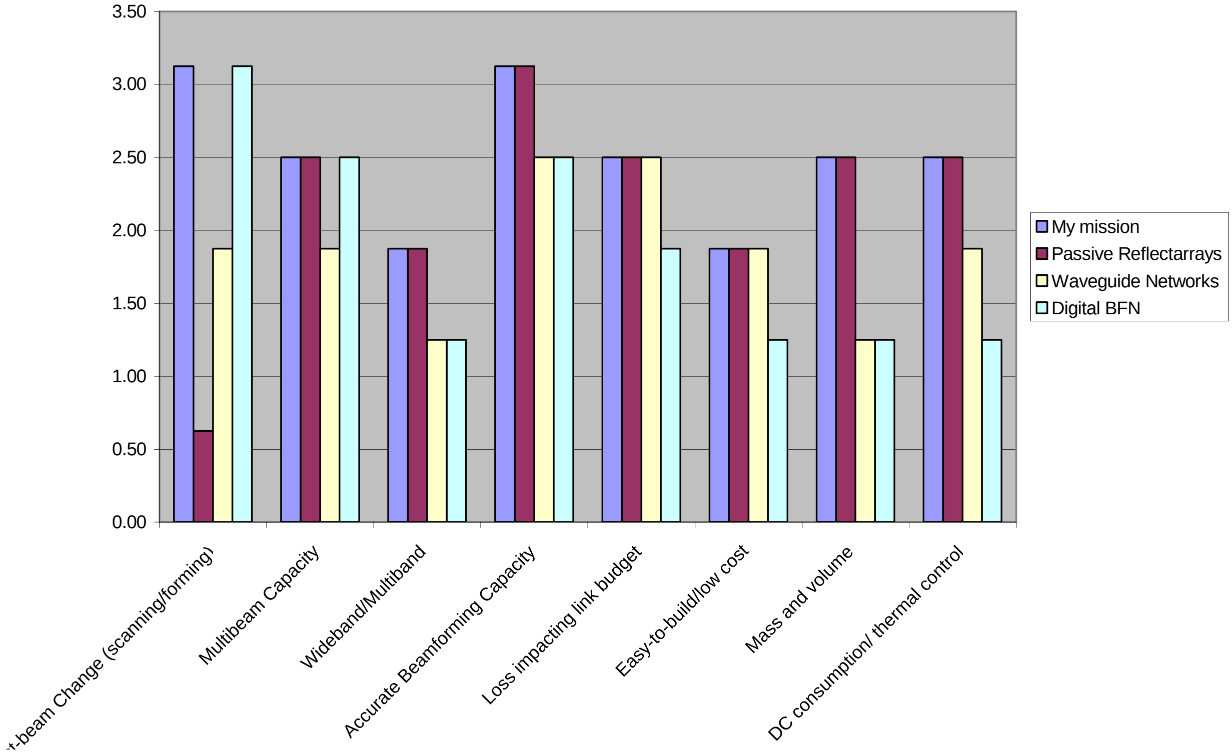


Figure 5-5 : Comparison of performances of various beamforming techniques with regards to mission requirements (advantages/drawbacks)

Finally, various beamforming methods can be quoted and compared on this kind of graphical exploitation , 20 being here the maximum normalised mark.

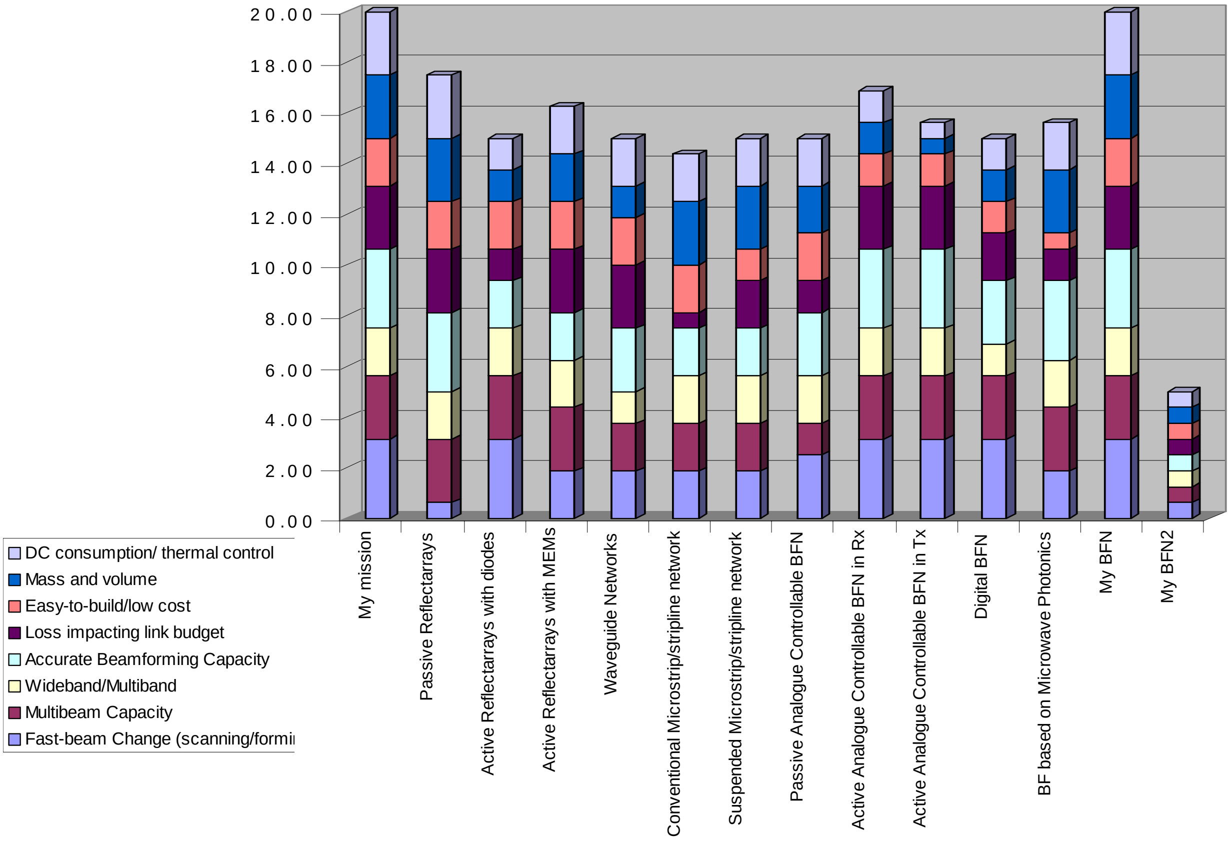


Figure 5-6 : Comparison of suitability of various beamforming techniques to a particular mission

However, this last kind of exploitation should be considered as indicative but not “absolute results”, because of the variations of performances of each beamforming techniques. This shall be used as an indication of the solution that shall be studied in priority for a given mission.

6 REFERENCES

We here list all references used and quoted during ACE A2.4 activity. This rather long list intends give a bibliographical database concerning various beamforming methods.

6.1 Reflectarrays

[1] J.A. Encinar, "Design of two-layer printed reflectarrays using patches of variable size", IEEE Trans. on Antennas and Propag. Vol. 49, June 2001.

[2] J. A. Encinar, J. A. Zornoza, "Broadband design of three-layer printed reflectarrays", IEEE Transactions on Antennas and Propagation. . Vol. 51, July 2003.

[3] J. Huang and R.J. Pogorzelski, "Microstrip reflectarray with elements having variable rotation angles", in IEEE Antennas and Propagation Society International Symposium, pages 1280 - 1283, July 1997.

[4] Eduardo Carrasco, Beatriz Alfageme, José A. Encinar,"Design of a multilayer aperture-coupled cell used as phase shifter in reflectarrays", 13 Journess Internationales de Nice sur les Antennes (JINA), Niza, Francia, Nov. 2004.

[5] S. Datthanasombat, Jr. Prata, A., P. Brown, O. Quintero, S. Spitz, and E. Rodríguez, "Spiral microstrip patch element for reflectarrays", in Antennas and Propagation Society, 2001 IEEE International Sym, pages 721 - 724, July 2001.

[6] R.E. Zich, M. Mussetta, M. Tovaglieri, P. Pirinoli, M. Orefice, "Design and experimental validation of microstrip reflectarray**",** *Proceedings of ICEAA'03*, Torino, Italy, Sept. 2003, pp. 209 – 212.

[7] J. A. Encinar, "Printed circuit technology multi-layer planar reflector and method for the design thereof", European Patent EP 1 120 856 A1, June 1999.

[8] J. A. Encinar, "Printed circuit technology multi-layer planar reflector and method for the design thereof", European Patent EP 1 120 856 A1, June 1999.

[9] J. Huang, "Analysis of a microstrip reflectarray antenna for microspacecraft applications", TDA progress report, http://techreports.jpl.nasa.gov, pp.153-173, Feb. 1995.

[10] C. Chekroun et al. "ReflectArray à balayage électronique pour Radar sur microsatellite", submitted for JINA Conference, 2004, Nice, France.

[11] R.J. Richards, E.W. Dittrich, O.B. Kesler, and J.M. Grimm. "Microstrip phase shifting reflect array antenna". Patent US 6020853 (Feb. 2000).

[12] R.J. Richards. "Integrated microelectromechanical phase shifting reflect array antenna". Patent US 6195047. (Feb. 2001).

[13] Béatrice Pinte, et al. "A reflectarray Antenna in Ka band with MEMS control", ANTEM 2004, July 2004

[14] E. Girard, R. Moulinet, R. Gillard, H. Legay. "An FDTD optimization of a circularly polarized reflectarray unit cell", in IEEE Antennas and Propagat. Intl. Symposium, pages 136 - 139, 2002.

[15] R. Gilbert. "Dipole tunable reconfigurable reflector array". Patent US 2001/0050650 (Dec. 2001).

[16] H.-P. Hsu and T.-Y. Hsu. "Optically controlled RF MEMS switch array for configurable broadband reflective antennas". Patent US 6417807 (Jul. 2002).

[17] J. R. Profera, E. Charles, “Active reflectarray antenna for communication satellite frequency re-use”, US patent 5280297, Jan. 1994.

[18] M.E. Bialkowski, A.W. Robinson, H.J. Song. “Design, development, and testing of X-band amplifying reflectarryas”, in IEEE Trans. on Antennas and Propagat., pp. 1065 – 1076. Aug. 2002.

[19] F. Gautier, et al., “phased reflector array and an antenna including such an array,” US patent 5148182, Sept. 1992.

[20] R.R. Romanofsky, J.T. Bernhard, F.W. van Keuls, F.A. Miranda, G. Washington, and C. Canedy. “K-band phased array antennas based on $Ba_{0.60}Sr_{0.40}Tio_3$ thin-film phase shifters”, IEEE Transactions on Microwave Theory and Techniques, pages 2504 - 2510, (Glenn Res. Center, NASA Lewis Res. Center, Cleveland, OH, USA) Dec. 2000.

[21] S. Müller, P. Scheele, C. Weil, M. Wittek, C. Hock and R. Jakoby: “Tunable Passive Phase Shifter for Microwave Applications Using Highly Anisotropic Liquid Crystals”, 2004 IEEE MTT-S International Microwave Symposium Digest, Vol. 2, Page(s):1153 – 1156, June 6-11, 2004.

[22] R. Marin, A. Mössinger, J. Freese, S. Müller and R. Jakoby – “Basic Investigation of 35-GHz Reflectarrays and Tunable Unit-Cells for Beamsteering Applications”, accepted for the 35th European Microwave Conference, Paris, Oct. 2005.

[23] L. Boccia, F. Venneri et al. “Application of varactor diodes for reflectarray phase control”, in IEEE Antennas and Propagation Society Intl. Symposium, pages 132 - 135, 2002.

[24] J. Huang, “Analysis of a microstrip reflectarray antenna for microspacecraft applications”, TDA progress report, http://techreports.jpl.nasa.gov, pp.153-173, Feb. 1995.

[25] M. Lou, J. Huang, V. Feria, “Radar Applications” chapter 17 in the book edited by H. M. Jenkins “Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications”, AIAA, Inc. , pp. 449-462, 2001.

[26] V. Feria, J. Huang, and D. Cadogan, 3-Meter Ka-Band Inflatable Microstrip Reflectarray, *Millennium Conference on Antenna and Propagation AP2000*, Davos, Switzerland, April 9, 2000.

[27] J. Huang, and A. Feria, Inflatable Microstrip Reflectarray Antennas at X and Ka-band Frequencies, *Antennas and Propagation*, Orlando, FL, U.S.A., July 11-16, 1999.

[28] D.I. Wu, R.C. Hall, and J. Huang, “Dual-frequency microstrip reflectarray”, in Antennas and Propagation Society International Symposium, 1995. AP-S. Digest, pages 2128 - 2131, June 1995.

[29] J. A. Encinar, “Design of a dual frequency reflectarray using microstrip stacked patches of variable size”, Electronic Letters, Vol. 32, No. 12, . pp. 1049-1050, June 1996.

[30] W. Menzel, M. Al-Tikriti, and M.B. Espadas Lopez. “Common aperture, dual frequency printed antenna (900 MHz and 60 GHz)”. Electronics Letters, pages 1059 - 1060, Aug 2001.

6.2 Passive Feeding/Combining networks

[31] J. Wettergren, R.Petersson, M. Viberg, “Design and Analysis of the ASCAT antennas”, ICCEAA 99, Torino.

[32] M. Sierra-Pérez, J.L. Fernández-Jambrina, J.L. Masa-Campos ,J.M. Serna-Puente. “MONOPULSE SLOT WAVEGUIDE ARRAY ANTENNA IN 35 GHz BAND” Spanish URSI symposium and Cost-284 meeting Barcelona September 2004.

[33] M. Sierra Pérez, M. Vera Isasa ; A. García Pino, M. Sierra Castañer. “Synthesis of circularly polarised radial line slot array” 27th European Microwave Conference. ISBN 0 7803-4202-X, pp 573-578 Jerusalem, September 1997

[34] M. Sierra Pérez, J.M. Salamanca, M. Vera Isasa, M. Sierra Castañer. “Synthesis of circularly polarised multiprobe fed radial line slot array” IEEE Antennas and Propagation Society. ISBN 0 7803-4478-2, Atlanta, Georgia. USA, 21-26 June 1998

[35] B. Perpére, J. Hérault, “Flat and Thin Broadband Shared Aperture for Future Conformal Smart Skin”, Chester, UK-IST-039RSY-011, April 2003.

[36] M. Hassel, “Dual Frequency Patch Antennas for GPS Occultation Measurements”, ESA workshop 2002.

[37] E. Suter, A. Carlström, J.M. Baracco, J.R. Mosig, “A multilevel approach to the efficient mom analysis of large scale planar antennas”, AP 2000.

[38] J. Balcells. “Antenna Systems for the TerraSAR-X Transponder”, Diploma thesis at the University of Karlsruhe, August 2004.

[39] J. Freese, R. Jakoby, H.-L. Blöcher, J. Wenger, “Synthesis of microstrip series-fed patch arrays for 77 GHz-sensor applications”, 2000 Asia-Pacific Microwave Conference, 3-6 Dec. 2000, Pages:29 – 33.

[40] J.A. Encinar, et al. “Review of base-station array antennas developped by the UPM”, JINA 2004, Workshop on array antennas, Parallel session ACE/JINA, Nice, France, Nov. 2004

[41] J. Vassal’lo et al, “ARCO : A spanish contribution to the improvement of array and reflectarrays with beam control”, 28th ESA Antenna Workshop on Space Antenna Systems ans Technologies, Noordwijk (The Netherlands), 30 May-3 June 2005.

[42] M. Barba, J.E. Page, J.A. Encinar, J.R. Montejo, “Elevation radiation pattern shaping and control in broadband base station antenna arrays”, submitted to “18th International Conference on Applied Electromagnetics and Communications (ICECom 2005)”, 12-14 Oct 205, Dubrovnik, Croatia.

[43] Hall, P. S. and Hall, C. M., "Coplanar corporate feed effects in microstrip patch array design", IEE Proc., vol 135, pt H, no 3, June 1988, pp 180-186.

[44] Hall, P. S., Dahele, J. S. and James, J. R., "Design principles of sequentially fed wide bandwidth circularly polarised microstrip antennas", IEE Proc., pt H, Vol 136, no 5, Oct 1989, pp 381-389.

[45] Hall, P. S., "Application of sequential feeding to wide bandwidth circularly polarised microstrip patch arrays", IEE Proc., pt H, Vol 136, no 5, Oct 1989, pp 390-398.

[46] Vetterlein, S. J. and Hall, P. S. "Multiple Beam Microstrip Patch Array with Integrated Beamformer", IEE Proc. H, vol 138, no 2, April 1991, pp176-184.

[47] Hall, P.S. and Vetterlein,S.J., "Integrated Multiple Beam Microstrip Array" Microwave Journal, vol 35, no 1, Jan 1992.

[48] C.Metz, E. Lissel, A.F. Jacob, “Planar multi resolutionar antenna for automotive radar”, Proc. 31 EuMC 2001, vol.1, London, Sept. 2001, pp 335-338.

[49] J. Butler, R. Lowe, “Beamforming matrix simplifies design of electronically scanned antennas”, Electron. Des. Vol.9, no.7, pp. 170-173, April 1961.

[50] J. Blass, “The multi directional antennas: a new approach to stacked beams”, IRE Conv. Proc, vol.8, pt. 1, pp. 48.51, 1960.

[51] W. Rotman, R.F. Turner, “Wide angle microwave lens for line source applications”, IEEE Trans. Antennas Propag., pp. 623-632, Nov. 1963.

6.3 Digital Controllable Adaptive Beamforming

[52] L. Petterson, M. Danestig, U. Sjöström, “An experimental S-Band Digital Beamforming Array”, IEEE Aerospace ans ElectronicsSystems Magazine, Nov. 1997, pp 19-26.

[53] S.O. Brattström, “A C-Band Phased Array Antenna Using Digital Beamforming in a Surveillance Radar System”, Proc. Of IEEE International Symposium on Phased Array Systems and Technology, 2003, Boston, pp217-222

[54] A. Gustafsson et. Al., “A Very Thin and Compact Smart Skin X-Band Digital Beamforming Antenna”, Proc. 1st European Radar Conderence (EuRAD) 2004, pp 313-316, Oct 14-15, 2004, Amsterdam

[55] .M. Younis, Y. Venot, W.Wiesbeck “Active antenna array for forward looking SAR”, Proc. Millenium Conference on Antennas and Propagation AP’2000, Davos, Switzerland, April 2000

[56] . Sierra-Perez et.al. “Integration and measurements of an UMTS smart antenn” IEEE Antennas and propagation Society International Symposium, Monterrey, California, USA June 2004

[57] A. Dreher, N. Niklasch, F. Klefenz, A. Schroth, “Antenna and Receiver System with Digital Beamforming for Satelilte Navigation and Communications”, IEEE Transactions on Microwave Theory and techniques, Vol. 51, N° 7, July 2003

[58] .H. Steyskal “Digital Beamforming at Rome laboratoty” Microwave Journal, Feb. 1996, pp 100-126

[59] C. Guiraud, M. Maignan, D. Rousset, I Albert, C. Bazile, J.M. Lopez “Digital Beamforming for Flexible Space Antennas, Potentialities and Challenges” JINA’2004

[60] S. Applebaum “Adaptive Arrays”, IEEE transactions on Aerospace and Antennas and Propagation, Vol AP24, N°5, Sept 1976, pp 585-598

[61] R.J. Mailloux, “Array Failure Correction with a Digitally Beamformed Array”, IEEE Transactions on Antennas and Propagation, Vol 44, N° 12, Dec 1996

6.4 Beamforming based on Microwave Photonics

[62] M. Peruyero, “The current status of broadband wireless access and ideas on future development”, Broadband Fixed Wireless Access Workshop, 4th Concertation Meeting IST Area IV.5 Mobile/Wireless/Satellite, Brussels (BELGIUM), 2001.

[63] H. Xu, T. S. Rappaport, R. J. Boyle, and J. H. Schaffner, “38-GHz wide-band point-to-multipoint measurements under different weather conditions”, IEEE Comm. Lett., vol. 4, no. 1, pp. 7-8, 2000.

[64] L. C. Godara, “Applications of antenna arrays to mobile communications: part I”, Proc. of the IEEE, vol. 85, no. 7, pp. 1031-1060, 1997.

[65] J. Marti, J. L. Corral, F. Ramos, V. Polo and J. M. Fuster, “Millimetre-wave optical beamforming network for phased-array antennas employing optical upconversion and wideband chirped fibre gratings”, Electron. Lett., vol. 35, no. 7, pp. 517-518, 1999.

[66] S. Jeon, Y. Wang, Y. Qian, T. Itoh, "A novel smart antenna system implementation for broad-band wireless communications", IEEE Trans. Antennas Propagation, vol. 50, pp. 600-606, 2002.

[67] Butler, J., and Lowe, R., “Beam-forming matrix simplifies design of electronically scanned antennas”, Electron. Design, pp. 170-173, April 1961.

[68] Charczenko, W., Surette, M., Matthews, P., Klotz, H., Mickelson, A.R., “Integrated optical Butler matrix for beam forming in phased array antennas”, Optoelectronics Signal Processing for Phased-Array Antennas II, pp. 196-205, 1990.

[69] Surette, M.R., Hjelme, D.R., Mickelson, A.R., “An optically driven Phased Array antenna utilizing Heterodyne Techiques”, Journal of Lightwave Technology Vol 11 (9) pp. 1500-1509 September 1993.

[70] R. A. Soref, “Programmable time-delay devices”, Applied Optics, vol. 23, pp. 3736-3737, November, 1984.

[71] A.P. Goutzoulis, D.K. Davies , “Hardware compresive 2-D fiber optic delay line architecture for time steering of phased array antennas”, Applied Optics, vol 29, no. 36, pp. 5353-5359, December 1990.

[72] A.P. Goutzoulis, D.K. Davies, J.M.Zomp , “Development and field demonstration of a hardware-compresive fiber optic true-time-delay steering system of phased array antennas”, Applied Optics, vol. 33, no. 35, pp. 8173-8185 December 1994.

[73] D. T. K. Tong and M. C. Wu, “A Novel Multiwavelenght Optically Controlled Phased Array Antenna with a Programmable Dispersion Matrix”, IEEE Photonics Technology Letters, vol. 8, no. 6, pp. 812-814, June 1996.

[74] D. T. K. Tong and M. C. Wu, “Programmable dispersion matrix using Bragg fiber grating for optically controlled phased array antennas”, Electronic Letters, vol. 32, no. 17, pp. 1532-1533, 15th August 1996.

[75] D. T. K. Tong and M. C. Wu, “Multiwavelength Optically Controlled Phased-Array Antennas”, IEEE Transactions on Microwave Theory and Techniques, vol. 46, no. 1, pp. 108-115, January 1998.

[76] W. Ng, A. Walston, G. Tangonan, J. Newberg and J.J. Lee , “Wideband Fibre-Optic Delay Network for Phased Array Antenna Steering”, Electronics Letters, vol. 25, pp. 1456-1457, October 1989.

[77] W. Ng, A. Walston, G. Tangonan, J. Newberg, J.J. Lee and N. Bernstein, “The First Demonstration of an optically Steered Microwave Phased Array Antenna Using True-Time Delay”, Journal of Lightwave Technology, vol. 9, pp. 1124-1131, September 1991.

[78] P.R. Herczfeld, “Optically Controlled Phased Array System and Method”, U.S. Patent 4814774, 21st March 1989.

[79] Esman, R.D., Frankel, M.Y., Dexter, J.L., Goldberg, L., Parent, M., Stilwell, D., and Cooper, D. “Fiber-optic prism true time-delay antenna feed,” IEEE Photon. Technol. Lett., vol. 5, pp. 1347–1349, Nov. 1993.

[80] Corral, J.L., Marti, J., Regidor, S., Fuster, J.M., Laming, R. and Cole, M.J., “Continuously Variable True Time Delay Optical Feeder For Phased Array Antenna Employing Chirped Fiber Gratings”, IEEE Trans. Microw. Theory Tech/J. Lightwave Technol. Special Issue on Microwave Photonics, 1997, 45, (8), pp. 1531-1536.

[81] Lembo, L.J., Holcomb, T., Wickham, M., Wisseman, P., and Brock, J.C., “Low-loss fiber optic time-delay element for phased-array antennas” Proceedings of the SPIE - The International Society for Optical Engineering 2155, 13-23 (1994).

[82] B. Vidal, D. Madrid, J.L. Corral, J. Martí, “Novel Photonic True-Time Delay Beamformer based on the Free Spectral Range Periodicity of Arrayed Waveguide Gratings and Fiber Dispersion”, Photonic Technology Letters, vol. 14, no. 11, pp. 1614-1616, November 2002.

[83] B. Vidal, J. L. Corral, M. A. Piqueras, J. Martí, "Optical Delay Line Based on Arrayed Waveguide Gratings' Spectral Periodicity and Dispersive Media for Antenna Beamforming Applications", IEEE Journal of Selected Topics in Quantum Electronics, vol. 8, no. 6, pp. 1202-1210, November/December 2002.

[84] M.K. Smit, "New Focusing and Dispersive Planar Component based on an Optical Phased Array", Electronics Letters, vol. 24, no. 7, pp. 385-386, March 1988.

[85] C. Dragone, "An NxN Optical Multiplexer Using a Planar Arrangement of Two Star Couplers", IEEE Photonics Technology Letters, vol. 3, no. 9, pp. 812-815, September 1991.

[86] C. Dragone, C.A. Edwards and R.C. Kistler, "Integrated Optics NxN Multiplexer on Silicon", IEEE Photonics Technology Letters, vol. 3, no. 10, pp. 896-899, October 1991.

[87] OBANET Project, "Beamformer Choice", Deliverable D2.2, 31th March 2001.

[88] OBANET Project, "Performance evaluation of single beam beamformers (transmitting and receiving modes) in the 40 GHz band", Deliverable D5.1, 31st October 2001.

[89] R. Eggemann, G. Grosskopf, E. Patzak, D. Rohde, "Experimental Investigations of a Novel Optical Delay Network Structure for True Time Delay Antennas at 10 GHz", Microwave Photonics, 1999. MWP '99. International Topical Meeting on
17-19 Nov. 1999 Page(s):161 - 164 vol.1

6.5 ACE Questionnaires

[90] ACE 2.4 Questionnaire Answer #8, "ERIEYE airborne early warning radar", Joakim Johansson, Ericsson Microwave Systems, Sweden.

[91] ACE 2.4 Questionnaire Answer #9, "ARTHUR artillery location radar", Joakim Johansson, Ericsson Microwave Systems, Sweden.

[92] ACE 2.4 Questionnaire Answer #10, "GIRAFFE AMB air surveillance radar", Joakim Johansson, Ericsson Microwave Systems, Sweden.

[93] ACE 2.4 Questionnaire Answer #11, "ERASP space radar", Christian Renard, Thales, France.

[94] ACE 2.4 Questionnaire Answer #12, "ALABAMA multifunction antenna", Joël Herault, Thales Airborne System, France.

[95] ACE 2.4 Questionnaire Answer #13, "Conical conformal satellite array", Gerard Caille, Alcatel Space, France.

[96] ACE 2.4 Questionnaire Answer #14, "STENTOR DRA satellite array", Gerard Caille, Alcatel Space, France.

[97] ACE 2.4 Questionnaire Answer #15, "FAFR with DBF focal plane array", Roland Baudin, Alcatel Space, France.

[98] ACE 2.4 Questionnaire Answer #17, "Remote sensing satellite array", Hans Ekström, Saab Ericsson Space, Sweden.

[99] ACE 2.4 Questionnaire Answer #18, "GPS occultation satellite array", Hans Ekström, Saab Ericsson Space, Sweden.

[100] ACE 2.4 Questionnaire Answer #19, "Dual-pol SAR satellite array", Hans Ekström, Saab Ericsson Space, Sweden.

[101]ACE 2.4 Questionnaire Answer #21, "DIGANT radar testbed", Lars Pettersson, FOI, Sweden.

[102]ACE 2.4 Questionnaire Answer #23, "AMALIA Radar testbed", Aziz Ouacha, FOI, Sweden.

[103]ACE 2.4 Questionnaire Answer #24, "TSA array EW testbed", Aziz Ouacha, FOI, Sweden.

[104] ACE 2.4 Questionnaire Answer #25, "Near range radar antenna", Michael Thiel, DLR, Germany.

[105] ACE 2.4 Questionnaire Answer #26, "SAR", Michael Thiel, DLR, Germany.

[106] ACE 2.4 Questionnaire Answer #27, "Satellite navigation", Michael Thiel, DLR, Germany.

[107]ACE 2.4 Questionnaire Answer #28, "TerraSAR-X Ground based satellite calibrator", Sergey Sevskiy, Uni Karlsruhe, Germany.

[108] ACE 2.4 Questionnaire Answer #29, "Airborne communication antenna", Sergey Sevskiy, Uni Karlsruhe, Germany.

[109]ACE 2.4 Questionnaire Answer #30a, "Conformal Antenna for Inmarsat Satellite", Sergey Sevskiy, Uni Karlsruhe, Germany.

[110]ACE 2.4 Questionnaire Answer #31, Small array testbed, Jens Freese, TU Darmstadt, Germany

[111]ACE 2.4 Questionnaire Answer #32b, "Satellite terminal Rx Antenna", Gerald Moernaut, KU Leuven, Belgium.

[112] ACE 2.4 Questionnaire Answer #33, "Reflectarray", Mario Orefice, Politecnico di Torino, Italy.

[113]ACE 2.4 Questionnaire Answer #34, "Base station antenna prototype", Mario Orefice, Politecnico di Torino, Italy.

[114]ACE 2.4 Questionnaire Answer #38, "Reflectarray", José A. Encinar, Univ Politécnica de Madrid, Spain.

[115] ACE 2.4 Questionnaire Answer #39, "Block elements", José A. Encinar, Univ Politécnica de Madrid, Spain.

[116] ACE 2.4 Questionnaire Answer #40, "IFF antenna array", Manuel Sierra Pérez, Univ Politécnica de Madrid, Spain.

[117]ACE 2.4 Questionnaire Answer #41, "Tactical communication horn array", Belén Galocha, Univ Politécnica de Madrid, Spain.

[118] ACE 2.4 Questionnaire Answer #42, "Satellite broadcast antenna", Manuel Sierra Pérez, Univ Politécnica de Madrid, Spain.

[119]ACE 2.4 Questionnaire Answer #43, "Primary radar antenna array", Manuel Sierra Pérez, Univ Politécnica de Madrid, Spain.

[120]ACE 2.4 Questionnaire Answer #44, "Mobile phone basestation antenna", Manuel Sierra Pérez, Univ Politécnica de Madrid, Spain.

[121]ACE 2.4 Questionnaire Answer #45, "Basestation for broadband access", Juan L. Corral, Univ Politécnica de Valencia, Spain.

[122]ACE 2.4 Questionnaire Answer #47, "APAR, Naval defence radar (4 planar arrays)", Lucas Van Ewijk, TNO, The Netherlands.

[123]ACE 2.4 Questionnaire Answer #49, “MiniSAR active X-band small array”, Lucas Van Ewijk, TNO, The Netherlands.

[124]ACE 2.4 Questionnaire Answer #50, “Active integrated”, Peter Hall, Univ of Birmingham, United Kingdom.

[125] ACE 2.4 Questionnaire Answer #51, “Corporate patch arrays”, Peter Hall, Univ of Birmingham, United Kingdom.

[126] ACE 2.4 Questionnaire Answer #52, “Multibeam patch arrays”, Peter Hall, Univ of Birmingham, United Kingdom.

[127] ACE 2.4 Questionnaire Answer #53, “Sequentially rotated patch arrays”, Peter Hall, Univ of Birmingham, United Kingdom.

6.6 Other ACE references

[128]ACE Annex I, “Description of Work”.

[129]ACE 2.4 Review, “Review of Array Architectures Used in Base Stations”, UPM, Spain.

[130]ACE 2.4 Review, “Review on Antenna Technologies for Commercial and Civil Radar Applications”, Jens Freese and Rolf Jakoby, TUD, and Josef Wenger, DaimlerChrysler AG, Germany.

[131]ACE 2.4 Review, “Review of State-of-the-Art in Spaceborne Arrays”, Gerard Caille, Alcatel Space, France.

[132]ACE 2.4 Review, “Review of State-of-the-Art in Defence Radar Applications”, Roland Bolt, TNO, Neth-erlands, and Lars Pettersson, FOI, Sweden.

[133]ACE 2.4 Review, “Review on User Terminal Arrays”, Michael Thiel, DLR, Germany

7 LIST OF ACRONYMS

ADC Analog-to-digital converter
ATC Air Traffic Control
BFN Beam-forming network
DBF Digital beam-forming
DLR Deutsches Zentrum für Luft- und Raumfahrt E.V.
EMW Ericsson Microwave Systems AB
G/T Gain to temperature ratio
LNA Low-noise amplifier
MEMS Micro-electromechanical systems
MMIC Monolithic Microwave Integrated Circuit
N/A Not applicable (*or* not available)
NoE Network of Excellence
PoliTo Politecnico di Torino
RX Receiver, or “receive mode”
SSPA Solid State Power Amplifier
TBC To be confirmed/checked
TNO Netherlands Organisation for Applied Scientific Research
TRL Technology readiness level
TTD True Time Delay (wideband scanning method)
TUD Technische Universität Darmstadt
TX Transmitter, or “transmit mode”
UKARL Universität Karlsruhe
UPM Universidad Politecnica de Madrid
UPV Universidad Politecnica de Valencia
USi Universita degli studi di Siena
WP Workpackage

