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New Antenna Array Architectures for Satellite Communications

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1. Introduction

Ground stations which integrate the control segment of a satellite mission have as a common feature, the use of large reflector antennas for space communication. Apart from many advantages, large dishes pose a number of impairments regarding their mechanical complexity, low flexibility, and high operation and maintenance costs. hus, reflector antennas are expensive and require the installation of a complex mechanical system to track only one satellite at the same time reducing the efficiency of the segment (Torre et al., 2006).
With the increase of new satellite launches, as well as new satellites and constellation of low earth orbit (LEO), medium earth orbit (MEO), and geostationary earth orbit (GEO), the data download capacity will be saturated for some satellite communication systems and applications. Thus, the feasibility of other antenna technologies must be evaluated to improve the performance of traditional earth stations to serve as the gateway for satellite tracking, telemetry and command (TT&C) operation, payload and payload message or data routing (Tomasic et al., 2002). One alternative is the use of antenna arrays with smaller radiating elements combined with signal processing and beamforming (Godara, 1997).
Main advantages of antenna arrays over large reflectors are the higher flexibility, lower production and maintenance cost, modularity and a more efficient use of the spectrum. Moreover, multi-mission stations can be designed to track different satellites simultaneously by dividing the array in sub-arrays with simultaneous beamforming processes. However, some issues must be considered during the design and implementation of a ground station antenna array: first of all, the architecture (geometry, number of antenna elements) and the beamforming process (optimization criteria, algorithm) must be selected according to the specifications of the system: gain requirements, interference cancellation capabilities, reference signal, complexity, etc. During implementation, deviations will appear as compared to the design due to the manufacturing process: sensor location deviation and sensor gain and phase errors (Martínez & Salas, 2010). In an antenna array, the computation of a close approach of the direction of arrival (DoA) and the correct performance of the beamformer depends on the calibration procedure implemented.

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This chapter is organized with the following sections. Section 2, introduces the relationship between applications and antenna design architectures. Section 3, introduces the new antenna array architectures for satellite communication including motivation and explains experimental examples. Section 4, explains adaptive antenna array and receiver architectures for adaptive antennas systems considering the beamforming with synchronization algorithms. Finally, Section 5 explains the A3TB concept.

2. Applications and antenna design architectures

In recent effort, new antenna array architectures have been under analysis and development. In (Tomasic et al., 2002) a highly effective, multi-function, low cost spherical phased array antenna design that provides hemispherical coverage is analyzed. This kind of novel architecture design, as the geodesic dome phased array antenna (GDPAA) presented in (Tomasic et al., 2002) preserves all the advantages of spherical phased array antennas while the fabrication is based on well-developed, easily manufacturable, and affordable planar array technology (Liu et al., 2006; Tomasic, 1998). This antenna architecture consists of a number of planar phased sub-arrays arranged in an icosahedral geodesic dome configuration.

In contrast to the about 10 *m* diameters dome of the GDPAA, there is the geodesic dome array (GEODA) (Sierra et al., 2007) with 5 *m* diameters dome. This antenna, presented in Fig. 1, has two geometrical structure parts. The first one, is based on a cylinder conformed by 30 triangular planar active arrays, and the second is a half dodecahedron geodesic dome conformed by 30 triangular planar active arrays. The GEODA is specified in a first version for satellite tracking at 1.7 GHz, including multi-mission and multi-beam scenarios (Martínez & Salas, 2010). Subsequently, the system of the GEODA has been upgraded also for transmission (Arias et al., 2010).



a b c

Fig. 1. a) The GEODA, b) The active sub-array demonstration, and c) The 45 elements planar active sub-array.

The antenna arrays technology in the user segment for satellite communications will substitute reflectors providing a more compact and easy to install antenna system, which is an interesting solution e.g. for satellite on the move (SOTM) system. There is a great diversity of solutions for fixed and mobile satellite communication systems including a large number of applications. Inmarsat broadband global area network (Inmarsat-BGAN) (Franchi et al., 2000) is the most representative example among mobile satellite systems (MSS), which gives land, maritime and aeronautical high speed voice and data services with global coverage using GEO satellites at L-band.

MSS services are divided into two groups, those that offer a regional coverage usually with GEO satellites, and those which offer a global coverage based on LEO or MEO satellite constellations. Depending on the coverage, there are some examples for MSS with regional coverage as the mobile satellite system (MSAT) in EEUU, Canada and South America, Optus in Australia, N-Star in Japan, Asia cellular satellite (ACeS) in Asia or Thuraya in the Middle East and in the North of Africa. While for MSS of global coverage there are some examples as Iridium, ICO Global Communications, Globalstar, Teledesic, etc. (Evans, 2009; Wu, 1994). Most of the MSSs work at L and S band, new applications on satellite to mobile terminal links work at X, Ku and Ka band, and satellite to base station connections work at L, S and C band. A number of applications is broad and lead terrestrial telecommunications market to offer a wider coverage: high speed voice and data (internet access, SMS, VoIP), digital video broadcasting by satellite 2 (DVB-S2) and digital video broadcasting satellite services to handhelds (DVB-SH), global position system (GPS) and Galileo, security, control and machinery monitoring on ships and aircrafts, teleeducation or telemedicine.

These modern satellite communications systems require new antenna solutions for base stations, aeronautical applications or personal communications services (PCS) on-the-move (Fujimoto & James, 2001). Within these applications, antenna array systems are potentially the best choice due to, as discussed above, its capability to perform electronically steering or beamforming, increase the antenna gain, and conform over curved or multifaceted surfaces the radiating elements. Portable antennas for PCS must be easy to install and mechanically robust, besides compact and lightweight (García et al., 2010) as the antenna array presented in Fig. 4.a. The design of antenna systems to provide high data rates for reliable PCS boarded on ships is not so strict in term of the geometrical requirements because it does not have space limitations (Geissler et al., 2010). However, in the case of land or airborne vehicles, geometrical and mechanical constraints are more severe. Antennas for terrestrial vehicles must be low profile, and for airborne vehicles aerodynamic shapes must be considered (Baggen et al., 2007; Vaccaro et al., 2010). Moreover, for the civil market conformal antenna arrays (Schippers, 2008; Kanno et al., 1996), or multi-surface arrays (Khalifa & Vaughan, 2007) are suitable choices to deal with the system aesthetic partiality.

Technological challenges have been faced during the implementation of satellite communication systems in the last decades. The design of a Test-Bed flexible and modular for testing or debugging beamforming algorithms and receiver architectures is an invaluable contribution in the educational, research and development area on satellite communication systems. The adaptive antenna array Test-Bed (A3TB) concept is based on the use of antenna arrays with beamforming capability to receive signals from LEO satellites (Salas et al., 2008). The scope of the A3TB is to probe the concept of antenna arrays applied to ground stations instead of reflectors for different applications, such as telemetry data downloading. It is also a good chance for Universities and Research Centers aiming to have their own ground station sited in their installations.

The A3TB ground station relies on the use of an antenna array to smartly combine the received signals from the satellite thanks to the implementation based on software defined radio (SDR) technology. The advantages of the SDR implementation is that A3TB architecture can be used to process any received signal from LEO satellites in the band imposed by the radio frequency (RF) circuits. Moreover, most of the processing is performed in software, so that appropriate routines can be used to process any received signal. The A3TB can be used to analyze the feasibility of different receivers and beamformer

algorithms, regarding the capability to switch the receiver architecture in terms of the synchronizer algorithm configuration (Salas et al., 2007).
The current version has been developed to track The National Oceanic and Atmospheric Administration (NOAA) satellites in the very high frequency (VHF) band, in particular, the automated picture transmission (APT) channel (Salas et al., 2008). Previous versions of A3TB dealt with low rate picture transmission (LRPT) signals from the meteorological operational satellite-A (MetOp-A), where a complete receiver with beamforming and synchronization stages has been implemented (Salas et al., 2007; Martínez et al., 2007).

3. Antenna arrays for satellite communications

Satellite applications require compactness, lightweight and low cost antenna systems to be mounted on a terrestrial vehicle, an aircraft or a ship, or as a portable man-pack or a handset, and to be competitive against ground systems. Its major advantage is the possibility of getting a wider or even a global coverage. For such purposes, antenna arrays offer the technology to get a directive system whose steering direction can be electronically and/or mechanically controlled. However, planar arrays usually cannot steer more than 60^{o}-70^{o} from the normal direction of the antenna (Mailloux, 2005). Thus, when a wider angular coverage is required conformal arrays are an appropriate option (Josefsson & Persson, 2006). Arrays can approximate conformal shapes, such as spheres or cylinders, using several planar arrays, simplifying fabrication of active components (Sierra et al., 2007).
Since the low cost and low weight specifications are of importance, micro-strip antennas are mostly used, due to its capacity to be printed over a dielectric substrate with photolithography techniques. Low cost and low permittivity substrates are usually used such as FR4 or PTFE with different quantities of glass or ceramic impurities. For more demanding applications, ceramics, like alumina or high/low temperature co-fired ceramics (HTCC/LTTC) allow the use of smaller components thanks to its high permittivity, and give robustness against mechanical stresses and high temperatures.

3.1 Geodesic antenna array for satellite tracking in ground station

The aim of using a single antenna for tracking many satellites at the same time avoiding mechanical movements as well as its inexpensive cost make these antennas an alternative to be considered (Salas et al., 2008). Multi-beam ability and interference rejection are facilitated thanks to the electronic control system of such antennas that improves the versatility of the ground stations.
The GEODA is a conformal adaptive antenna array designed for MetOp satellite communications with specifications shown in Table 1. This antenna was conceived to receive signals in single circular polarization (Montesinos et al., 2009). Subsequently, in recent efforts the system has been upgraded also for transmission and double circular polarization (Arias et al., 2010). Hence, operating at 1.7 GHz with double circular polarization it can communicate with several LEO satellites at once in Downlink and Uplink. Current structure is the result of a comprehensive study that valued the ability to cover a given spatial range considering conformal shape surface and a given beamwidth (Montesinos et al., 2009). As Fig. 1 shows, GEODA structure consists of a hemispherical dome placed on a cylinder of 1.5 meters height. Both cylinder and dome are conformed by 30 similar triangular planar arrays (panels). Each panel consists of 15 sub-arrays of 3 elements (cells). The radiating element consists of 2 stacked circular patches with their own

RF circuits. The principal patch is fed in quadrature in 2 points separated 90º in order to obtain circular polarization. The upper coupled patch is used in the aim of improving the bandwidth.

Each panel is able to work itself as an antenna since they have a complete receiver that drives the 1.7 GHz signal to an analog to digital converter (ADC). In order to adapt the signal power to the ADC, it is mandatory to implement a complete intermediate frequency (IF) receiver consisting of heterodyne receiver with an automatic gain control block. Hence, each triangular array has active pointing direction control and leads the signal to a digital receiver through an RF conversion and filtering process. To follow the signal from the satellite, the main beam direction has to be able to sweep an angle of 60º. In this way, it is needed a phase shift in the feeding currents of the single radiating element. Previous calculations have demonstrated that 6 steps of 60 degrees are needed to achieve the required sweeping angle. An adaptive digital system allows the adequate signal combination from several triangular antennas. The control system is explained in (Salas et al., 2010).

Parameter	Specification	Parameter	Specification
Frequency range [GHz] **Tx:** **Rx:**	 1.65 to 1.75 1.65 to 1.75	**Isolation between Tx and Rx [dB]**	>20
Polarization	Dual circular for Tx and Rx bands	**VSWR**	1.2:1
G/T [dB/K] **For elevation >30º** **For elevation 5º**	 3 6	**SLL [dB]**	-11
EIRP [dBW]	36	**Size [m]**	1.5x1.5x3
3dB beamwidth [deg.]	5	**Accuracy steering [deg.]**	±1.4
Maximum gain [dBi]	29	**Coverage [deg.]:** **Azimuth** **Elevation**	 360º >5º
Efficiency [%]	50		

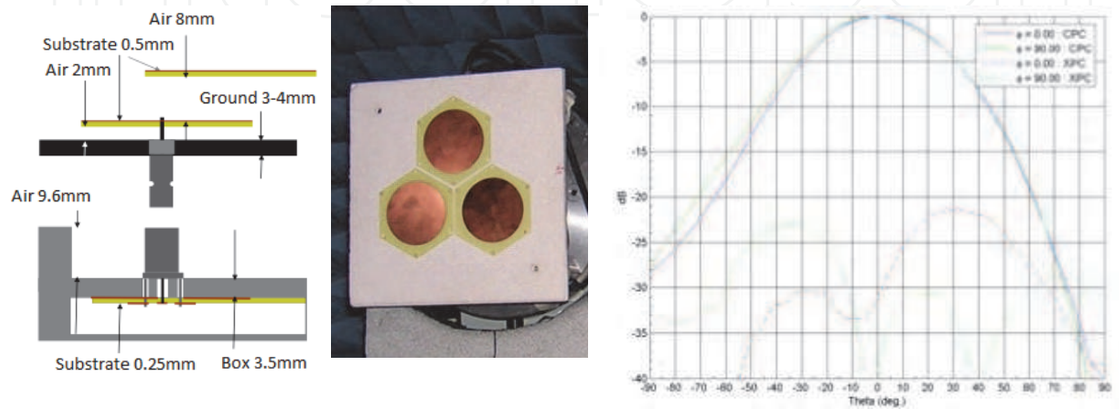
Table 1. Main specifications for GEODA antenna.

3.1.1 Cell radiation pattern

Based on the study presented in (Sierra et al., 2007), the single radiating element is a double stacked circular patch that works at 1.7 GHz with 100 MHz bandwidth. In order to obtain circular polarization, the lower patch, which has 90 mm diameter, is fed by 2 coaxial cables in quadrature. Both coaxial cables connect the patch with a hybrid coupler to transmit and

receive signals with both, right and left, circular polarizations. The upper patch is a circular plate with 78.8 mm diameter, and it is coupled to the lower patch increasing the bandwidth by overlapping both resonant frequencies tuning the substrate thickness and the patch diameter size. Fig. 2.a shows the radiating element scheme and main features of the layer structure are specified in (Montesinos et al., 2009).

A cell sub-array of 3 radiating elements shown in Fig. 2.b is considered the basic module to build the planar triangular arrays. The whole cell fulfills radiation requirements since it has a good polar to crosspolar ratio and a very low axial ratio. Likewise, as it is presented in Fig. 2.c, the radiation pattern shows symmetry and low side lobes for full azimuth.



a b c

Fig. 2. a) Assembly of the single radiating element, b) Cell scheme, and c) Cell radiation pattern.

3.1.2 Transmission and Reception (T/R) module and cell distribution

Different T/R module configurations have been considered, providing either single or double polarization (Arias et al., 2010). T/R module allows amplifying and controlling the phase shift between signals, received and transmitted, providing an adaptive beam and steering direction controller in the whole working pointing range. As Fig. 3 shows, the design implemented contains a hybrid coupler, enabling double circular polarization; a double pole double throw (DPDT) switch, selecting polarization associated with transmission and reception way; 2 low noise amplifiers (LNAs), which amplify the signal received or transmitted; a single pole double throw (SPDT) switch, choosing transmission or reception way; and phase shifters, introducing multiples of 22.5º relative shift phases to form the desired beam. These surface mount devices have been chosen in order to reduce space and simplify the design.

Signals transmitted/received by the 3 T/R modules placed in a cell are divided/combined thanks to a divider/combiner circuit composed of 3 hybrid couplers that leads the signal to a general T/R module where signal is amplified. Due to transmission and reception duality, 2 SPDT switches are used to select the amplification way. Furthermore, each T/R module has associated a -25dB directional coupler that is used to test T/R modules in the transmission mode. Additionally, reception mode is tested by measuring signal in the divider/combiner circuit. A single pole 6 throw (SP6T) switch selects the path that is tested.

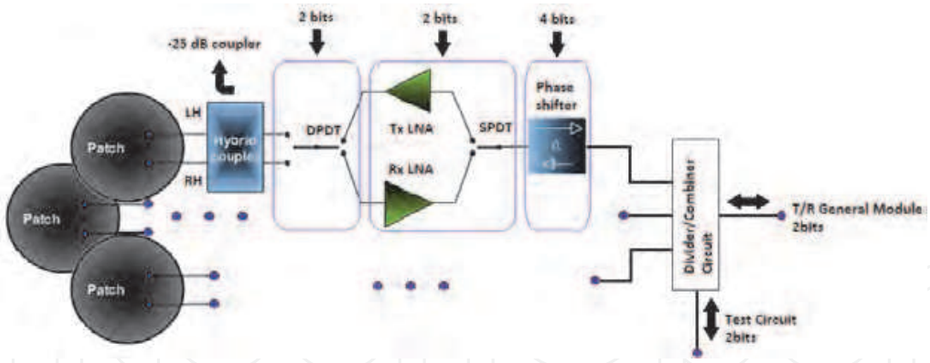


Fig. 3. Cell sub-array and RF circuit.

3.1.3 Control system

The control system has two main parts (Salas et al., 2010), the hardware structure and the control software. The two level hardware structure has the lowest possible number of elements, making the control simpler in contrast to the previous in (Salas et al., 2010). Finally, an inter-integrated circuit (I2C) expander is used to govern T/R modules individually, and one more cover cell needs (LNA of call and test). A multipoint serial standard RS-485 is used to connect the computer with the panels.

3.2 Portable antenna for personal satellite services

New fix and mobile satellite systems (Evans, 2000) require antenna systems which can be portable, low profile and low weight. Planar antennas are perfect candidates to fulfill these specifications. Usually slots (Sierra-Castañer et al., 2005) and printed elements (García et al., 2010) are most used as radiating elements.

3.2.1 Antenna system structure

In this subsection it is introduced a printed antenna for personal satellite communications at X band, in Fig. 4. Table 2 shows main antenna characteristics.

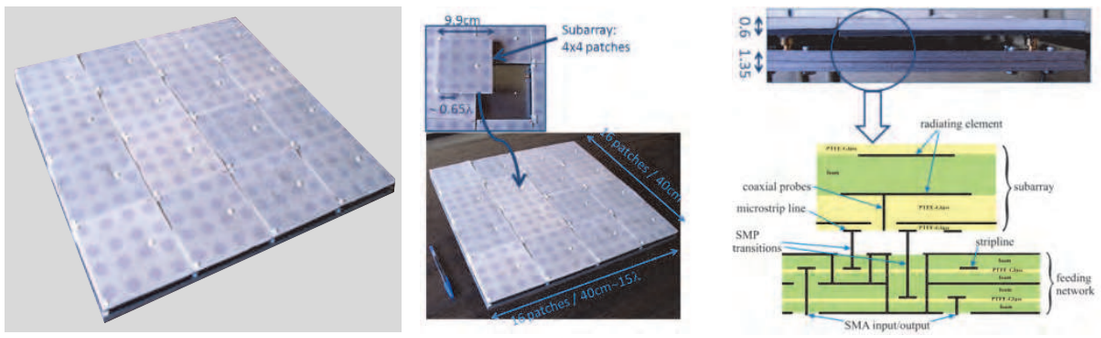
Parameter	Specification	Parameter	Specification
Frequency range[GHz] **Tx:** **Rx:**	 7.9 to 8.4 7.25 to 7.75	**Efficiency [%]**	50
Polarization	Dual circular polarization for Tx and Rx bands	**Isolation between Tx and Rx [dB]**	>17
G/T [dB/K]	7	**VSWR**	1.4:1
EIRP [dBW]	32	**SLL [dB]**	-11
3dB beamwidth [deg.]	5	**Size [m]**	40x40x2.5
Maximum gain [dBi]	25	**Weight [Kg]**	2

Table 2. Portable antenna specifications.

This is a planar, compact, modular, low loss and dual circular polarized antenna, for Tx and Rx bands, simultaneously. It is made up by a square planar array of 16x16 double stacked micro-strip patches, fed by two coaxial probes. A hybrid circuit allows the dual circular polarization (Garg et al., 2001). Elements are divided in 16 sub-arrays excited by a global power distribution network of very low losses, minimizing the losses due to the feeding network and maximizing the antenna efficiency. In order to reduce side lobe levels (SLL), the signal distribution decreases from the centre to the antenna edges, keeping symmetry with respect to the main antenna axes. The antenna works at X band from 7.25 up to 8.4 GHz with a 14.7% relative bandwidth for a 1.4:1 VSWR and a maximum gain of 25 dBi.

3.2.2 Sub-array configuration

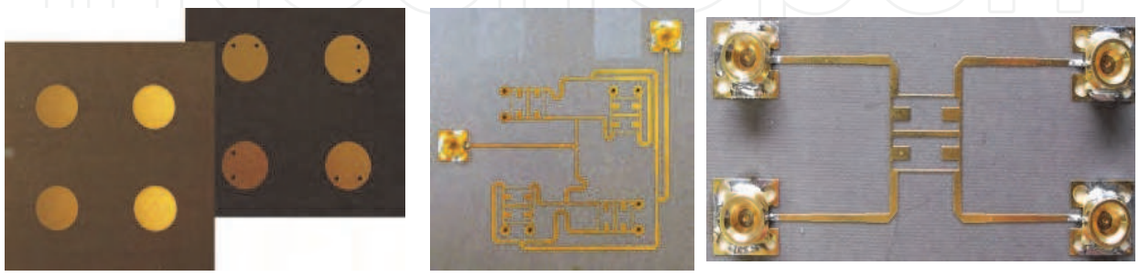
The sub-array configuration can be seen in Fig. 4.a. It makes possible to separate the fabrication of these sub-arrays from the global distribution network, simplifying the corporative network and getting a modular structure suitable for a serial fabrication process. Each sub-array is a unique multilayer board, where PTFE-Glass substrate of very low losses has been used as base material. The power distribution network is connected to each sub-array through (SMP-type) coaxial connectors.



a b c

Fig. 4. a) Dual polarized portable printed antenna for satellite communication at X band, b) Sub-array perspective view, and c) Side view and multilayer scheme.

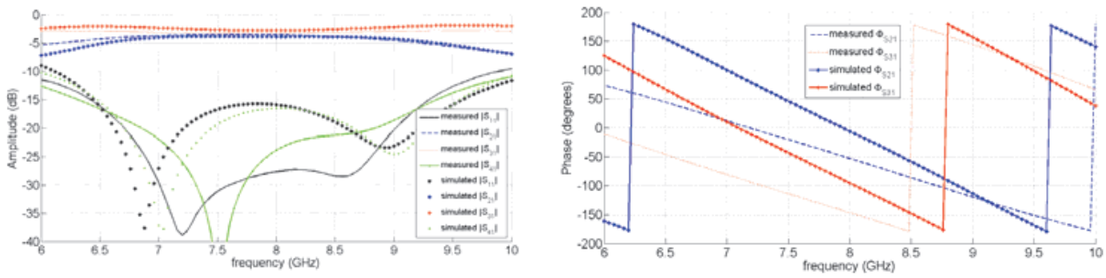
Fig. 5.a and Fig. 5.b show the sub-array unit cell. In order to obtain better polarization purity, each element is rotated 90º and excited by a 90º phase-shifted signal. Moreover, in Fig. 5.c is showed a miniaturized branch-line coupler (BLC) of three branches working as a wide band hybrid circuit (García et al., 2010; Tang & Chen, 2007).



a b c

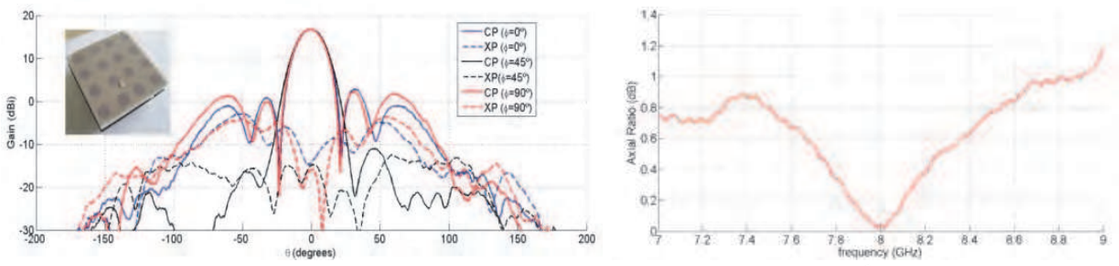
Fig. 5. Unit cell test board, a) Unit cell test board 2x2 stacked patches, b) Micro-strip feeding network, and c) Miniaturized BLC Prototype.

A conventional configuration takes up an area of 13.3 cm² which is big compared to the radiating element and the sub-array subsystem size. Therefore, a miniaturization of the BLC is needed using the equivalence between a λ/4 transmission line and a line with an open-ended shunt stub. An area reduction about 35% is achieved and the hybrid circuit behaves like a conventional BLC. In Fig. 6.b and Fig. 6.c measurement results for the BLC in Fig. 5.c are shown compared with simulations.
Fig. 7 depicts some sub-array measurements. The copular to crosspolar ratio is better than 25 dB and axial ratio is under 0.9 dB in the whole bandwidth.



a b

Fig. 6. Miniaturized BLC, Measured and simulated S-parameters in: a) Amplitude, and b) Phase.

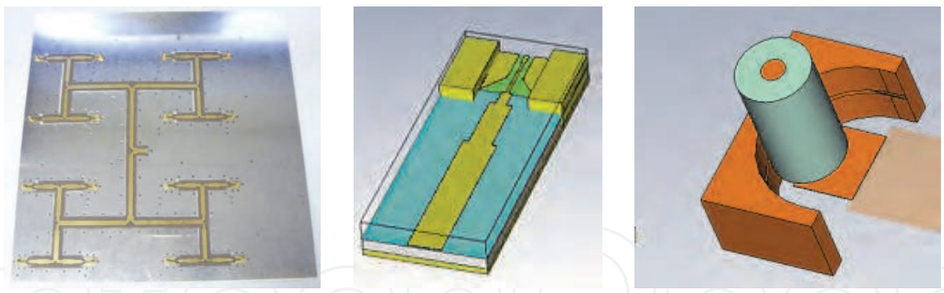


a b

Fig. 7. 4x4 patch sub-array measurements, a) Radiation pattern at 7.75 GHz, and c) Axial ratio for right-handed circular polarization.

3.2.3 Low losses power distribution network

The global feeding network presented in Fig. 8.a is a protected strip-line, where foam sheets of high thickness are used to get low losses. Such a kind of feeding network allows keeping a trade-off between the simplicity of exciting the radiating elements using printed circuits and the loss reduction when the distribution network is separated in a designed structure to have low losses. Losses in the structure are around 0.6 dB/m which yields to 0.3 dB of losses in the line. Two global inputs/outputs using SMA-type connectors, one for each polarization, excite the strip-line networks.
Vertical transitions have to be treated carefully and must be protected to avoid undesired higher order mode excitation. Thereby, it has been design a short-ended pseudo-waveguide, adding some extra losses about 0.3 dB, for two kinds of vertical transitions, as can be seen in Fig. 8.b and Fig. 8.c.

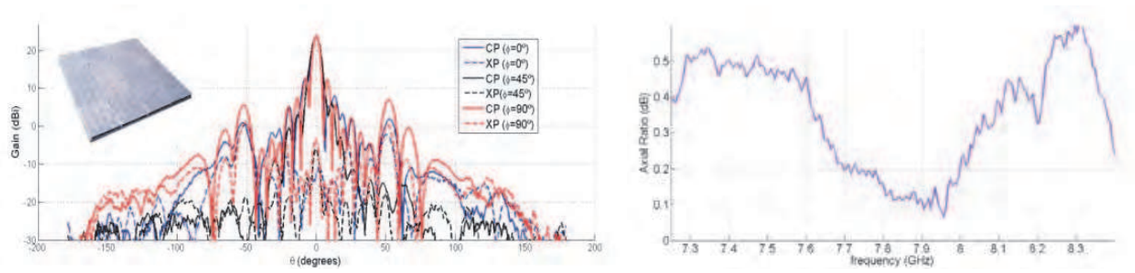


a b c

Fig. 8. a) Protected strip-line global corporative network for one polarization, b) Transitions from strip-line to SMA-type connector, and c) Transitions from strip-line to SMP-type connector.

3.2.4 Antenna performance

Fig. 9 depicts measured radiation pattern at 7.75 GHz, gain and axial ratio for the antenna system. It is shown a maximum gain of 25 dBi in the lower band and about 22 dBi in the upper band, and a SLL around 11 dB. Copolar to crosspolar ratio is better than 30 dB and axial ratio is under 0.7 dB. Total losses are about 4 dB in the working band.



a b

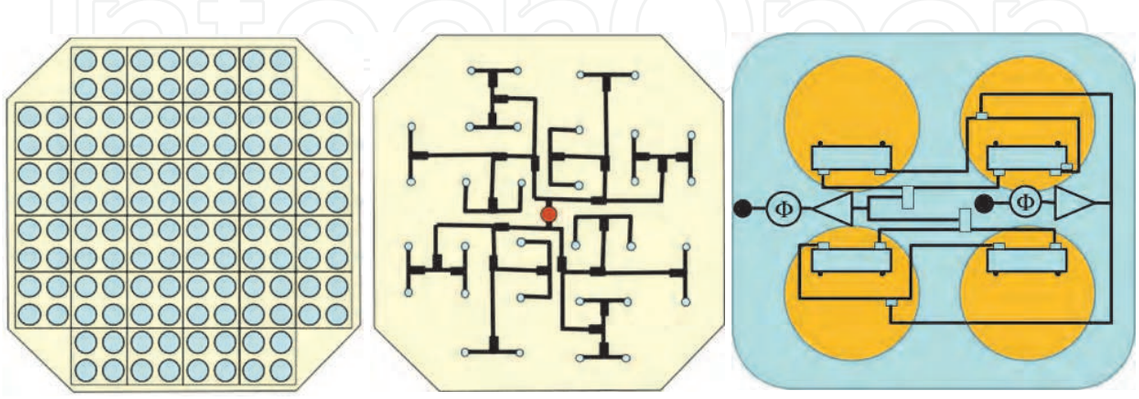
Fig. 9. Antenna measurements results, a) Radiation pattern at 7.75 GHz, and c) Axial ratio for right-handed circular polarization.

3.3 Electronically steerable antennas for mobile and fixed portable systems

At present, two types of electric steerable antenna systems can be used to access the satellite communication services (Bialkwoski et al., 1996). These are: fixed position portable systems and mobile systems such as those installed on a land vehicle. The fixed portable antenna system is relatively easy to be accomplished by the antenna designer. The design involves standard procedures that concern the operational bandwidth, polarization and moderate gain (García et al., 2010). One drawback of the fixed position portable system is that they require the user to be stationary with respect to the ground. This inconvenience can be overcome with the mobile antenna system. A mobile user complicates the scenario since the ground mobile antenna needs to track the satellite (Alonso et al., 1996). The design of such a system is more challenging as new features associated with the mobility of the system have to be incorporated (Fernández et al., 2009). The requirement leads to a narrow beamwidth, for which satellite tracking is required as the vehicle moves around. Electronically steerable antennas enable the development of reconfigurable antennas for satellite applications.

3.3.1 Steerable antenna for fixed position portable systems

This antenna is a fixed satellite communication system with high gain at X band, consisting of an antenna array that integrates 32 2x2 sub-array modules in the complete antenna, as shown in Fig. 10.a. It is a planar and dual circular polarized antenna for Tx and Rx bands simultaneously. It is made up by a planar array of double stacked circular micro-strip patches, fed by 2 coaxial probes to generate circular polarization. A hybrid circuit allows the dual circular polarization as shown in Fig. 10.b.



a b c

Fig. 10. Active multi-beam antenna, a) Top view, b) Feeding network of the complete antenna, and c) Beamforming network of the 2x2 sub-array module

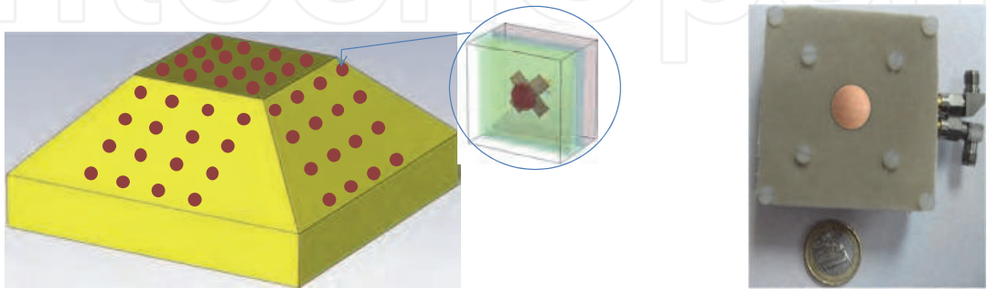
The antenna has the same design parameters, structure and configuration as the antenna explained in Section 3.2 but with a different feeding network, as previously shown. In this case, the beamforming network requires changes in the feeding phase in the 2x2 sub-arrays, which can be achieved by phase shifters (ϕ) associated with different sub-arrays (Fig. 10.c). All these sub-arrays are connected to a feeding network, in Fig. 10.b, formed by transmission lines with low losses in strip-line. General specifications of the steerable antenna for fixed position portable systems are provided in Table 3.(a).

3.3.2 Automatic steerable antenna for mobile systems

A broadband circularly polarized antenna for satellite communication in X band is presented in Fig. 11 and specified in Table 3.(b). The arrangement features and compactness are required for highly integrated antenna arrays. It is desired to get a low-gain antenna for mobile satellite communications with low speed of transmission. In this system, the antennas are formed by 5 planar 4x4 arrays of antennas, which form a truncated pyramid with a pointing capability in a wide angular range, so that among the 5 planar arrays the complete antenna can cover any of the relative positions between the mobile system and the satellite in a practical way. The scheme of the active antenna can be seen in Fig. 11.

As it can be observed in Fig. 11.a, the antenna terminal is a multi-beam printed antenna shaped as a trunk pyramid capable of directing a main beam in the direction of the satellite. The antenna steering system consists of a multi-beam feeding structure with switches that lets combine the feed of each 4x4 arrays to form multiple beams. Switching the different 4x4 arrays, it is achieved different multiple beams and the variation of the steering direction.

The complete antenna consists of a Tx and Rx module that works independently in the 2 frequency bands.
The antenna has multiple beams covering the entire space to capture the satellite signal without moving the antenna. The signal detected in each of the beams is connected to a switch, which, by comparison, is chosen the most appropriate 4x4 array. The steering direction of the 4x4 array can vary between a range of directions that covers a cone angle range of 90º. To obtain the required gain and cover the indicated range, it is required around 15 beams, which can be obtained by integrating the beamforming networks with switches in the design as presented in (Fernández et al., 2009).



a b

Fig. 11. Complete antenna structure, a) Radiating element of the 4x4 arrays, and b) Prototype top view.

The radiating element of the 4x4 array is one 2 crossed dipoles with a stacked circular patch as shown in Fig. 11.a and Fig. 11.b. In Fig. 12 the cross-section of the radiating element structure is presented.

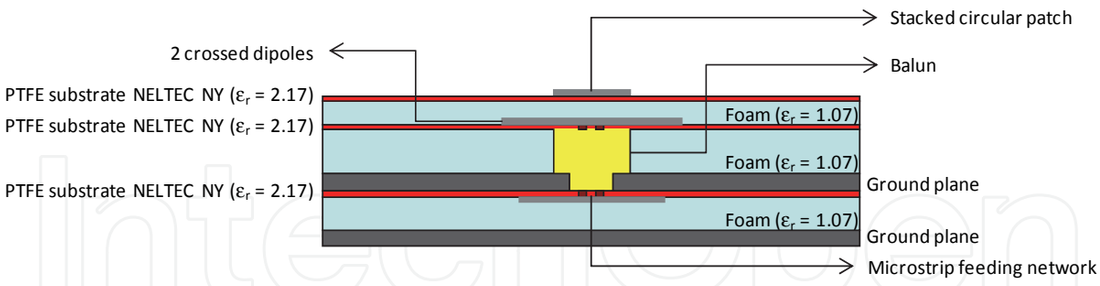
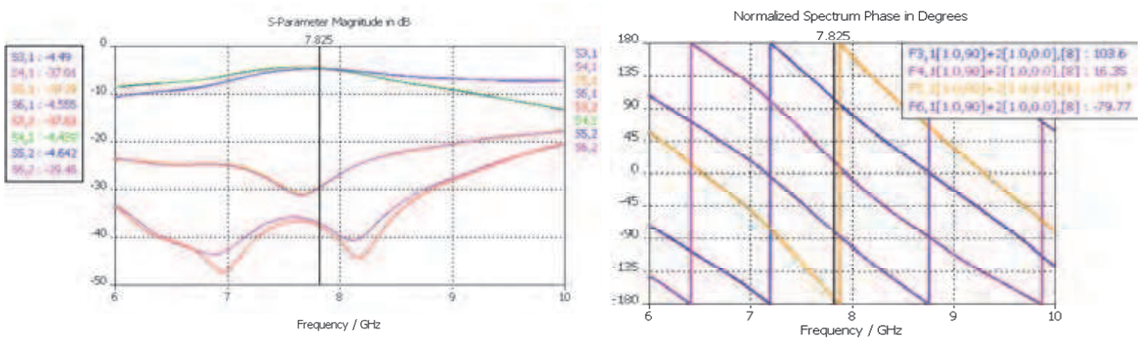


Fig. 12. Cross-section scheme of the radiating element.

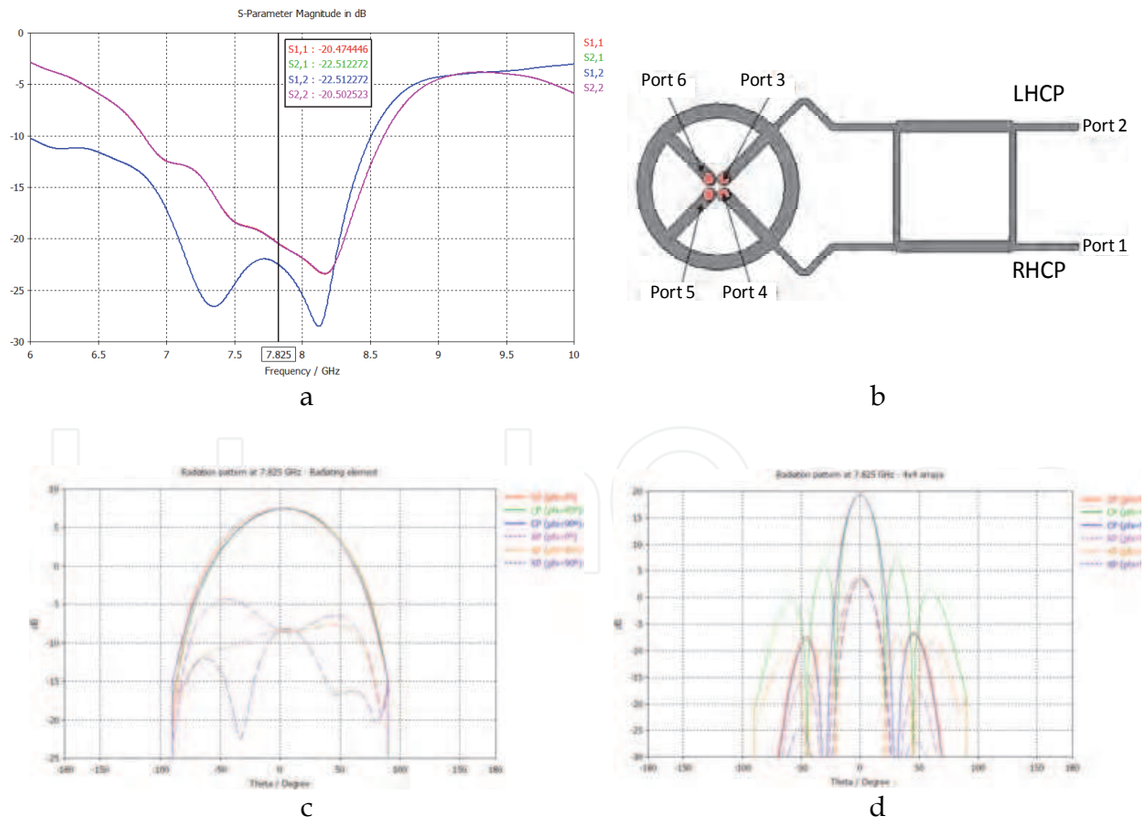
The key element of the radiating element feeding structure (Fig. 14.b) is a resonant micro-strip feed ring that has been implemented, as well as a micro-strip 90º branch-line coupler to obtain the desired right hand or left hand circular polarizations (RHCP or LHCP) which ensures adequate port coupling isolation. The S-parameters in amplitude and phase of the micro-strip feeding structure are shown in Fig. 13.a and Fig. 13.b.
Fig. 14.a depicts the S-parameters of the radiating element with the micro-strip feed structure and they fulfill the specification, in Table 3.(b). In Fig. 14.c, the radiation pattern of the radiating element at 7.825 GHz is shown and in Fig. 14.d the radiation pattern of the 4x4

arrays is presented. It is shown a maximum gain of 19.4 dBi at the center frequency band (7.825 GHz). Copolar (CP) to crosspolar (XP) ratio is better than 17 dB and the axial ratio is under -3dB.



a b

Fig. 13. Micro-strip feeding structure, a) Amplitude of S-parameters, and b) Phase of S-parameters.



a b c d

Fig. 14. a) S-parameters, b) Resonant ring + 90º branch-line coupler, c) radiation pattern at 7.825 GHz, and d) 4x4 array radiation pattern.

Parameter	Value (a)	Value (b)	Comments
Freq. range [GHz] **Rx** **Tx**	7.25 - 7.75 7.9 - 8.4	7.25 - 7.75 7.9 - 8.4	Microwave applications.
G/T (in Rx) [dB/K]	7	7	
EIRP (in Tx) [dBW]	32	32	
Beamwidth at -3dB [deg.]	4	20	
Polarization	circular	circular	In both, reception and transmission.
Gain [dBi]	>28	>15	
Axial ratio [dB]	< 1	<3	**(a)** Between ±50º. **(b)** Between ±45º.
VSWR	< 1.4:1 (-15.6 dB)	< 1.5:1 (-13.9 dB)	
Isolation between ports [dB]	< -17	< -15	
Radiation pattern [deg.]	±35	±90	Steering direction tilt.
Dimensions [cm]	40x40x4	20x20x15	

Table 3. (a) General specifications of the steerable antenna for fixed position portable systems , and (b) General features of the automatic steerable antenna for mobile systems.

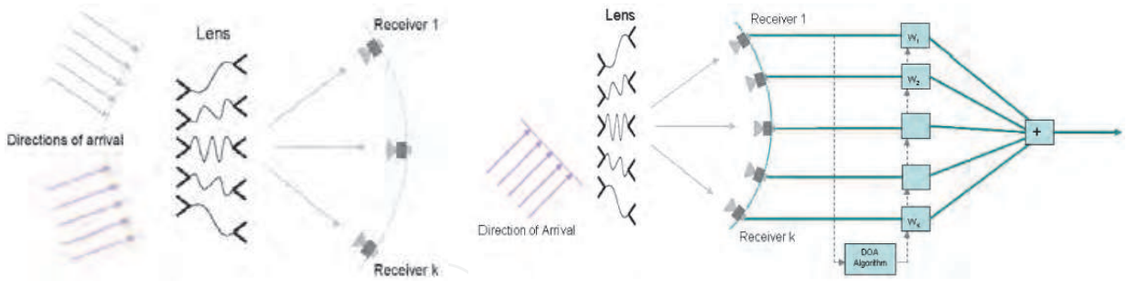
3.4 Transmit-array-type lens antenna for terrestrial and on board receivers

Technology in satellite communications has revealed an increasing interest in novel smart antenna designs. Phased-array based designs are basic in electronically reconfigurable devices for satellite applications, which are more and more demanding. The strict requirements in terms of architecture, shape and robustness are important constraints for the development of planar lens-type devices. Regarding the usage and location, lens-type devices are useful for either terrestrial or on board receivers, in vehicular technology. Some clear examples are satellite communications for aircrafts preserving the fuselage aerodynamics or for some other kind of vehicles such as trains, etc.

3.4.1 Introduction to lens-type structures

In a general view, in lens-type a particular signal is received (in our case, an electromagnetic wave with specific features in terms of frequency, wave-front, etc.), it is processed (either complex signal processing techniques or only phase correction tasks can be considered in this interface), and finally, the processed signal is retransmitted.

Regarding the lens configuration, a transmit-array lens consists of three well distinguished interfaces: the first one for signal reception, one interface for signal processing, and the last one for processed signal re-radiation, as depicted in Fig. 15.



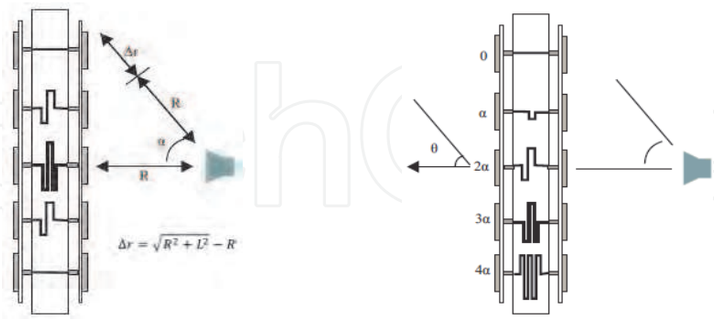
a b

Fig. 15. a) Multi-user scheme with different receivers and transmitters, and b) Adaptive scheme with DoA determination.

These structures are intimately related to reflect-array ones, where the reception and transmission interfaces are turned to be the same interface, with a reflection-type behavior (Encinar & Zornoza, 2001). Although in an equal output phase configuration a transmit-array device behavior would be similar to the one obtained with a reflect-array, the transmit-array offers the advantage of removing the feed blockage.
In a transmission scheme, depending on the transmitter position regarding the lens, a different steering direction is achieved and a different user is pointed. In the case of reception, the situation is the same: the user position configures the direction of arrival, which determines the receiver position around the lens (Padilla et al., 2010a). In adaptive schemes, applying the proper processing algorithm to the signal received in the different receivers around the lens, it is possible to develop an adaptive steering vector, in terms of the desired direction of arrival.

3.4.2 Transmit-array lens architecture and design

Lens-type structures provide two fundamental advantages. First, phase error correction due to spherical wave front coming from the feeding antenna. Fig. 16.a shows this effect. Second, new radiation patterns configuration. Fig. 16.b depicts this fact.



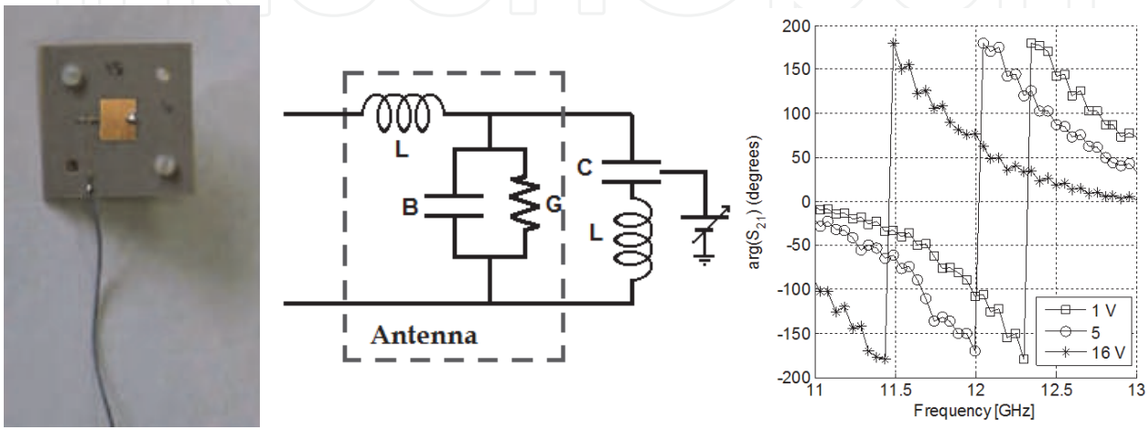
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Fig. 16. a) Phase error correction, and b) Radiation pattern reconfiguration.

3.4.3 Electronically reconfigurable devices for active transmit-array lenses

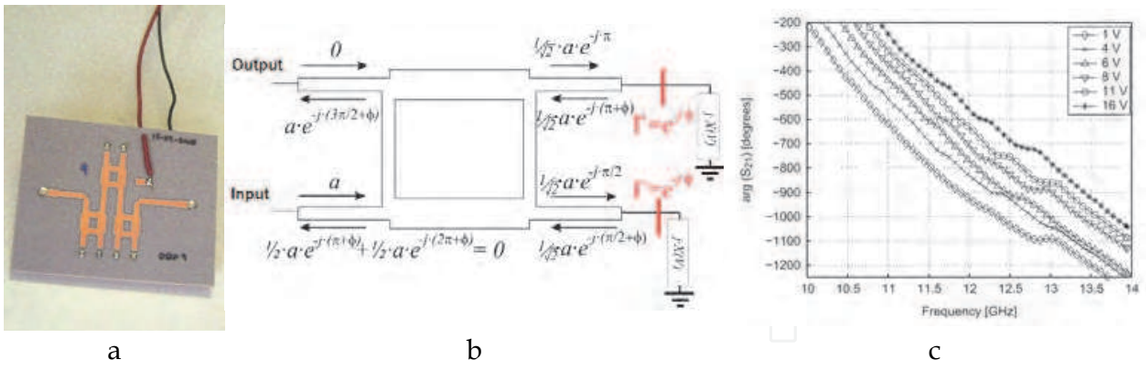
The addition of reconfigurability on transmit-array devices requires the possibility of controlling the phase response of the transmitted signal at each cell of the lens. Electronic control of phase signal may be added in two different ways: First, electronic tuning of the

radiating element phase response (Padilla et al., 2010a): Modifications in the radiating element circuital behavior lead to changes in phase response (arg[S_{21}]). Fig. 17 shows an electronically reconfigurable microwave patch antenna for this purpose, along with the equivalent circuit and prototype outcomes in terms of phase.
Second, electronic tuning of phase shifters in transmission lines (Padilla et al., 2010c): Modifications in the phase response of the phase shifters lead to corresponding changes in phase response. Some options are applied for these devices, such as hybrid couplers, etc. Fig. 18 shows a microwave phase shifter prototype for this purpose, along with the working scheme and its outcomes in phase.



a b c

Fig. 17. Electronically reconfigurable antenna, a) Patch antenna prototypes, b) Equivalent circuit, and c) Phase behavior in frequency.



a b c

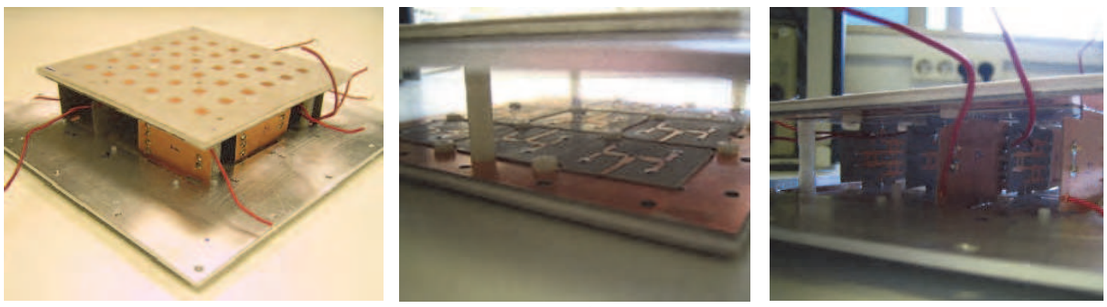
Fig. 18. Electronically reconfigurable phase shifter, a) Phase shifter prototype, b) Working scheme, and c) Phase behavior in frequency.

3.4.4 Electronically reconfigurable active transmit-array prototype

One electronically reconfigurable prototype is presented in Fig. 19 and detailed in this section. The prototype design implies the use of microwave phase shifters according to the design specified in section 3.4.3. This transmit-array lens prototype operates at 12 GHz. Main specifications are provided in Table 4.

Parameter	Value	Comments
Frequency range [GHz]	12 ± 0.5	Microwave applications.
Polarization	Linear	In both, reception and transmission.
Directivity [dBi]	>21	
Axial ratio [dB]	< 1	Between ±50º elevation.
S_{11} [dB]	< -20	
Radiation pattern [deg.]	±30	Steering direction tilt, for both H and V planes.
Feeding antenna [mm]	120	Corrugated horn linearly polarized
Phase shifters [deg.]	360	Full phase range variation.
Transmit-array elements	36	6x6 array topology.
Separation between elements	$0.7\lambda_0$	Related to the wavelength

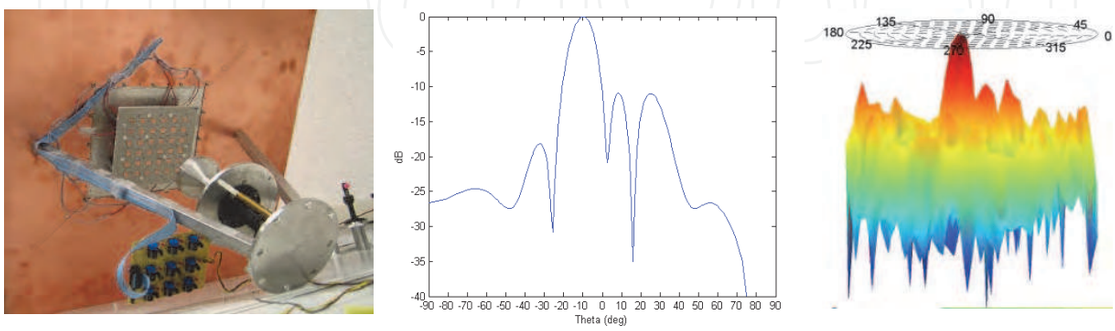
Table 4. Main features of the electronically reconfigurable transmit-array prototype.



a b c

Fig. 19. Transmit-array core, a) Transmit-array prototype, b) Distribution networks, and c) Phase shifter integration.

The electronically controllable steering capabilities are tested and assured for a range of ± 30ºin each main axis. An example of radiation pattern is provided in Fig. 20, for 9º tilt in one of the main axes.



a b c

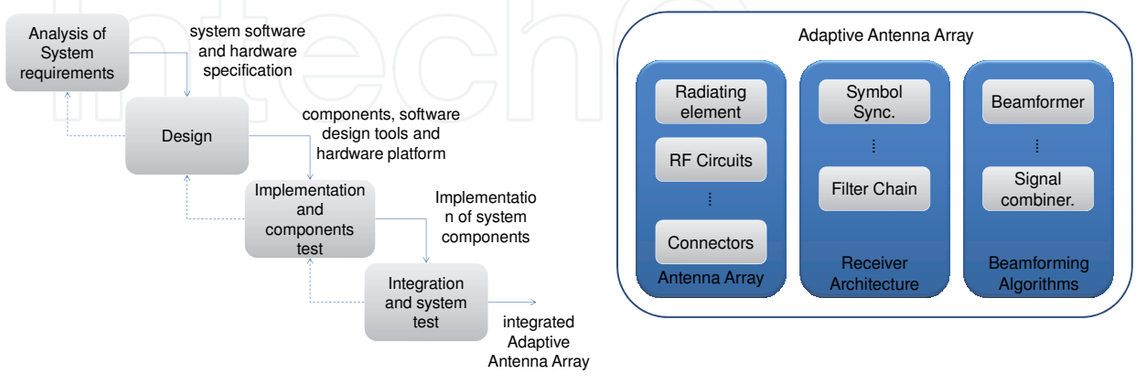
Fig. 20. a) Complete transmit-array with feeder and control circuits; and transmit-array measurement results for 9º tilt in one axis, b) H plane, and c) 3D plot.

4. Adaptive antenna array

Adaptive antennas can be described as systems usually based on three main parts: the antenna array, the receiver architecture and the beamforming scheme. Thus, adaptive antennas have those advantages owing to those three main parts. The system capabilities increase as complexity and development cost do. Furthermore, since signal processing is the basement of the adaptive antenna concept it is important to analyze the design challenges in terms of hardware architecture and components such as processors and embedded systems.
The antenna array provides the capability of performing the antenna pattern meeting the environment requirement under study. Besides, receiver architectures have some interesting advantages depending on the implemented receiver arraying technique such as signal to noise ratio (SNR) and bit error rate (BER) performance enhancement. Furthermore, symbol synchronization and carrier recovery can be used increasing the receiver complexity but providing higher performances. Finally, beamforming schemes use multiple antennas in order to maximize the strength of the signals being sent and received while eliminating, or at least reducing, interference as discussed in Section 4.3.
Adaptive antenna arrays are often called Smart Antennas because they have some key benefits over traditional antennas, by adjusting traffic patterns, space diversity or using multiple access techniques. The main four key benefits are: First, enhanced coverage through range extension by increasing the gain and steering capability of the ground station antenna; Second, enhanced signal quality through multi-target capability and reduction of interferences; finally, adaptive antennas improve the data download capacity in the ground segment of satellite communication by increasing the coverage range (Martínez et al., 2007).

4.1 Design and architecture based on software defined radio

For design there is the well known waterfall life cyclic model (Royce, 1970) that can be used to manage main aspects of the design of architectures. Thus, some tasks must be fulfilled subsequently as follow in Fig. 21.a.
Fig. 21.b shows the design schemes resulting of the requirement analysis stage corresponding software and hardware system specifications. In the depicted scheme, there are some system components such as the radiating element and RF circuits that are often designed under iterative prototyping model.



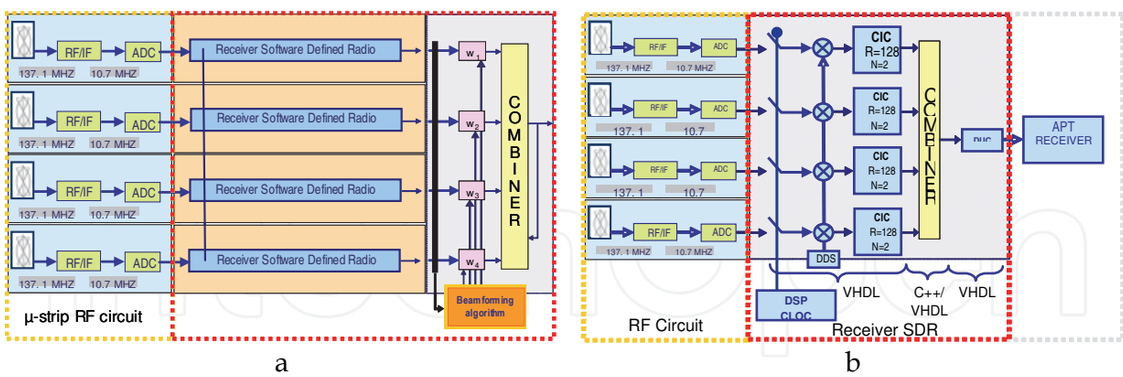
a b

Fig. 21. a) Water life cyclic model of the adaptive antenna array design, and b) Simplified design scheme of adaptive antenna arrays.

Regarding the hardware implementation, tables presented in (Martínez et al., 2007) show the hardware resource consumption in the field programmable gate array (FPGA) Virtex-4 for the least mean squared (LMS) beamforming algorithm with full spectrum combining (FSC) receiver architecture and SIMPLE beamforming algorithm with symbol combining (SC) receiver architecture. Both scheme designs have an antenna array of 2 elements. The algorithm based on correlation requires less hardware. The main difference can be appreciated in the amount of digital signal processing oriented component (DSP48) resources, typically used for filtering applications (Martínez et al., 2007).

4.2 Receiver architectures based on algorithms type

Several receiver architectures can be implemented, and they are frequently based on the type of the beamforming algorithm used. When training signals are available in the transmitted frame, a time-based reference algorithm can be used. However, this solution is only valid when the earth station is capable of demodulating the received training sequence. Other algorithms used in deep space communications are based on signal correlation and they avoid performing the demodulating process. This kind of algorithms are blind techniques that do not require any additional signal demodulation before applying some beamforming technique and work better in low SNR conditions than time-based algorithms. Several receiver architectures can be implemented exploiting the processing capabilities of the SDR, such as FPGA, application-specific integrated circuits (ASICS), and digital signal processing (DSPs). The design of the receiver architecture fundamentally depends on the selection of beamforming algorithms. An example of beamforming technique is the LMS algorithm whose estimation of coefficients or weights requires a temporal reference and is implemented through SC receiver architecture (Fig. 22.a). In the other hand, the SIMPLE algorithm (Rogstad, 1997) constitutes a beamforming technique that is implemented using FSC receiver architecture (Fig. 22.b) in order to perform the calculation of weights.



a b

Fig. 22. Comparison of receiver architectures. a) Symbol Combining (SC), and b) Full Spectrum Combining (FSC).

The SC architecture can be divided into two more sub-classes which work on a phase-recovery basis. The complex symbol combining (CSC) recovers the phase information with regard to a reference element using feed-forward and feedback algorithms. One of the advantages of this scheme is that the rate of data sent to the combining module has a rate slightly higher than the symbol rate. For most applications, the symbol rate is relatively low and is a multiple of the data rate. In this kind of schemes, there is an important cost

consideration in real-time applications and the requirements of instrumental phase stability are very severe (Rogstad et al., 2003). Other type of SC architecture is the stream symbol combining (SSC). In this kind of scheme, data are sent to the combining module at a rate equal to the symbol rate. The symbol rate depends on the coding scheme and for most applications is relatively modest. Also, the requirements of instrumental phase stability are no severe, as in the case of CSC scheme. The disadvantage of the SSC is the additional hardware required for each antenna.

Furthermore, there are the baseband combining (BC) and carrier arraying (CA) architectures discussed in (Rogstad et al., 2003). In BC architectures the signal from each antenna is carrier locked and combining in baseband for further demodulation and synchronization. In effect, the carrier signal from the spacecraft is used as a phase reference so that locking to the carrier eliminates the radio-frequency phase differences between antennas imposed by the propagation medium. Besides, in CA architectures, one individual carrier-tracking loop is implemented on each array element. Then, the elements branches are coupled in order to increase the carrier-to-noise ratio (CNR), but losses of radio channel are far compensated (Rogstad et al., 2003).

In general, the selection of the beamforming algorithms is determined by the following aspects: Hardware and computational resources; Speed of convergence and residual error of adaptive algorithms; Calibration requirements and auto-compensation ability; and system signal-transmission characteristics.

4.3 Beamforming techniques for satellite tracking

Some satellites transmit useful information inside its frames for synchronization and tracking purposes. The gathering of satellite data requires the tracking operation along its earth orbit. To accomplish this goal with adaptive array architectures, some beamforming techniques should be implemented. Fig. 23 illustrates a simple example of a narrowband linear adaptive beamformer system.

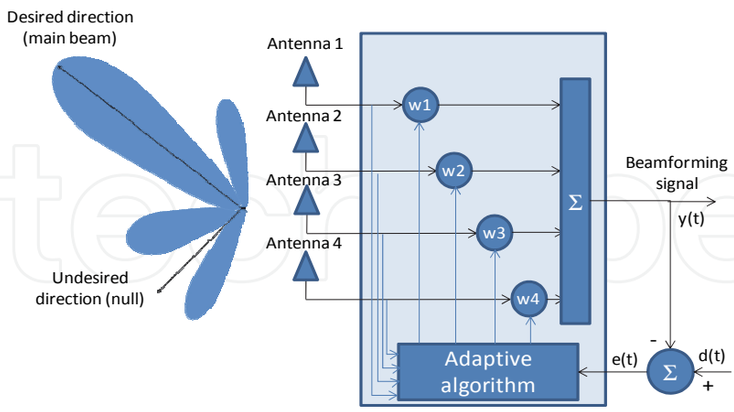


Fig. 23. Adaptive antenna system.

A linear beamformer combines signals according to some weights w_i, to produce a desired radiation pattern. The mathematical expression of a linear beamformer at the array output in vector notation can be expressed as $y = w^H x$, where x is the received signal vector to be combined, w are the weights computed by the beamforming algorithm and ^{H} denotes transposition and conjugate of $(\cdot)$.

In adaptive antennas design, weights are dynamically calculated with a certain algorithm in order to optimize some signal parameter like signal to interference-plus-noise ratio (SINR), SNR, or BER. An extended variety of algorithms exist in the literature for beamforming purpose and the most appropriated selection is done depending on the signal characteristics of the received signal.

4.3.1 Blind techniques

Blind beamformers make use of an inherent property of the received signal, such as the ciclo-stationarity of the constant modulus. In the latter, the algorithm eliminates the fluctuation of the signal amplitude and computes the weights to minimize the effect produced by those variations. The algorithms that make use of these methods are denoted as Constant Modulus Algorithms (CMA) (Biedka, 2001).

CMA algorithms present an important disadvantage: as the phase information is not considered, the constellation of quadrature phase shift keying (QPSK) signals commonly used in satellite communications appears rotated after beamforming, which imposes the need of an additional phase recovery subsystem in the array output.

4.3.2 Temporal-reference algorithms

Algorithms based on a temporal reference require a known reference included in the frame of the signal, such as training sequences, unique word (UW) or pilot bits. Thus, these schemes are normally used for digital signals. The aim of these beamformers is the minimization of the energy of an error signal integrated by interferences and noise. In order to reduce the order of the problem, the weight calculation is usually done iteratively.

The most popular adaptive filters are the LMS and Recursive Least Squares (RLS) algorithms (Haykin, 2002). Briefly, the main differences lie in the method to calculate and the final convergence behavior: while LMS has a linear complexity order with the number of antennas in the array, RLS makes use of matrix operation, so that the complexity order is quadratic, but the convergence is faster.

An interesting alternative to the LMS is the Normalized LMS (NLMS), which normalizes the adaptive step to avoid variation during the convergence process. The counterpart is the more intensive processing requirements to calculate signal power and normalization operation.

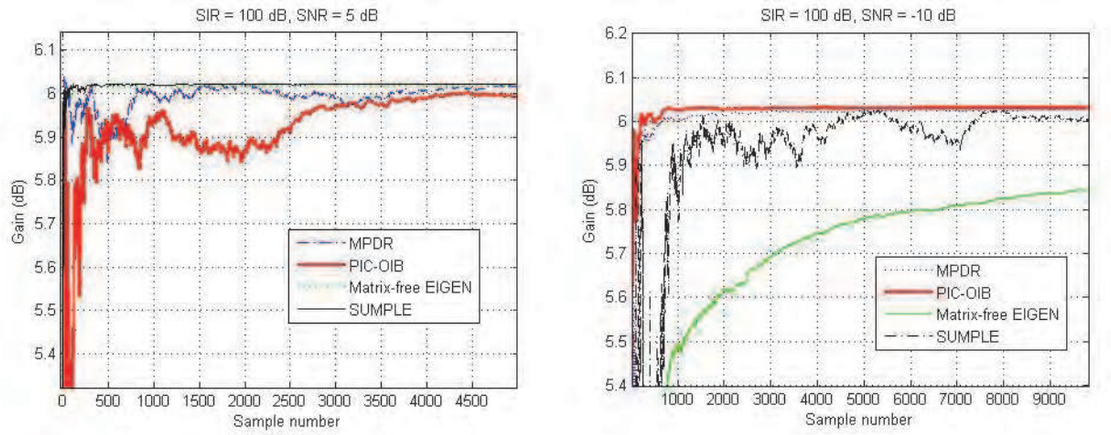
4.3.3 Correlation-based algorithm

In contrast to beamformers based on temporal reference, schemes based on signal correlation do not require the demodulation of any signal. These techniques are the most popular to extract the spatial information for beamforming, and we have focused on the use of the SIMPLE algorithm (Rogstad, 1997). This algorithm has been used by the Deep Space Network (DSN) of National Aeronautics and Space Administration (NASA) to combine the signals received from spatial probes in radio telescopes located in different sites around the Earth surface. The main disadvantage of correlation based schemes is the lack of ability to cancel interference signals.

4.4 Performance comparison

Some simulation comparisons between spatial and blind algorithms are presented to show benefits and drawbacks. Four algorithms have been selected with a 4-element uniform linear

array (ULA). The spatial algorithms simulated are post-beamformer interference canceller – orthogonal interference beamformer (PIC-OIB) (Godara, 2004) and minimum power distortionless response (MPDR) (Van Trees, 2002). On the other hand, the blind algorithms are the matrix-free EIGEN and the SUMPLE (Rogstad, 1997). The convergence process is compared as a function of the input SNR as depicted in Fig. 24.
As it can be observed from the above results, spatial algorithms outperform blind ones at low SNR, and vice versa. On the other hand, with medium-low SNR and low or absence of interferences, the behavior of all algorithms is quite similar.



a b

Fig. 24. Convergence behavior of spatial versus blind algorithms in the absence of interferences with several input SNR. a) SNR = 5 dB, and b) SNR = -10 dB.

5. Experimental Test-Bed based on SDR platform

This section presents a test platform known as Adaptive Antenna Array Test-Bed - A3TB, where a comparative study of several beamforming algorithms can be performed and modularity of the architecture is a well proved advantage. The test bed is based on SDR technology and uses a novel architecture that can be used with both blind and spatial-based beamforming algorithms. The A3TB concept can be applied to a number of scenarios as the current version is independent of the signal properties. Simulation results using the A3TB with the APT channel from NOAA satellites show the performance of the concept and the feasibility of the proposed implementation.
The scope of the system development was is to prove the concept of antenna arrays applied to ground stations instead of reflectors for different applications, such as telemetry data downloading or end-user in mobile applications as discussed in the introduction section. In contrast to reflector antennas, antenna arrays offer the possibility of electronic beam-steering avoiding the use of complex mechanical parts and therefore reducing the cost of the antenna. It is also a good chance for Universities and Research Centers aiming to have their own ground station sited in their installations.

5.1 A3TB concept

The A3TB can be defined as *a software-defined radio beamformer applied to a ground station for tracking LEO satellites*. The novelty relies on the use of an antenna array to smartly combine

the received signals from the satellite and its implementation based on SDR technology. The reason to use an antenna array instead of a single antenna is to electronically steer the beam in the direction of the satellite along its orbit without requiring a mechanical system for tracking. In addition to the advantages of the use of SDR technology and antenna array, it is the modularity and flexible architecture implemented in the A3TB. Fig. 25 shows the A3TB architecture where it is evident the feasibility to update or change during operation any of the main blocks. It is possible to change during operation the beamforming algorithm and to include new beamforming modules to the system. Furthermore, changes on the BENADC are possible to implement not during operation, but new receiver architecture at off-line such as those options discussed at follow.

In (Salas et al., 2007), the block diagram represents the software system implementation of the first version of the test-bed prototype and most of it is based on VHDL. Depending on the firmware, three options could be installed into the FPGA Virtex4. The option A is implemented with the signal processing on the PC, so the SIMPLE beamforming is done in the module developed in C++. The option B is implemented completely on VHDL and this option need to export the beamforming weights just to draw the array pattern diagram. Finally, in contrast to the option B, the option C is implemented for the LMS beamforming algorithm.

With the first version of the Test-Bed, the modularity on the selection of firmwares was proved switching between A, B or C receiver architectures, and an important result of the Test-Bed development is the hardware resources occupation presented in (Salas et al., 2007).

The advantage of the SDR implementation is that A3TB architecture can be used to process any received signal from a LEO satellite in the appropriate band imposed by the RF stages. Moreover, most of the processing tasks are performed on software, using appropriate routines to process any receive signal. There are 2 main schemes to implement the beamforming stage: SC and FSC [41]. Both schemes are compared in Section 4.2.

The current version of the A3TB in Fig. 25.a was updated to track NOAA satellites in the VHF band, in particular the APT channel. Previous versions of A3TB dealt with LRPT signals from MetOp-A, where a complete receiver with beamforming and synchronization stages has been implemented(Salas et al., 2007; Martínes et al., 2007).

5.2 Implementation of the A3TB

The A3TB prototype consists of 4 main parts as shown in Fig. 25.a. The first part is the antenna array, which has 4 crossed-dipole antennas as depicted in Fig. 25.b. The second part consists of RF-IF circuits which amplify and down convert to IF incoming signals. Furthermore, an automatic gain control (AGC) was implemented using two steps of variable attenuators in the IF domain.

The third part is the SDR platform which consists of the beamforming algorithms implemented on C++ and the FPGA firmware on VHDL, PC and BENADC blocks show in Fig. 25, respectively. The hardware resources occupation for this Test-Bed implementation is similar to one presented in (Martínes et al., 2007). The last part is the software from weather satellite signal to image decoder (WXtoImg) on the PC using the sound card output/input in order to get the weather satellite image.

Since the implemented architecture is FSC the demodulation is not required and the IF signal is digitized. For the signal processing hardware design the BenADC-v4 has been chosen. This solution includes a FPGA Xilinx Virtex4-SX55 with four 12-bit analog inputs at

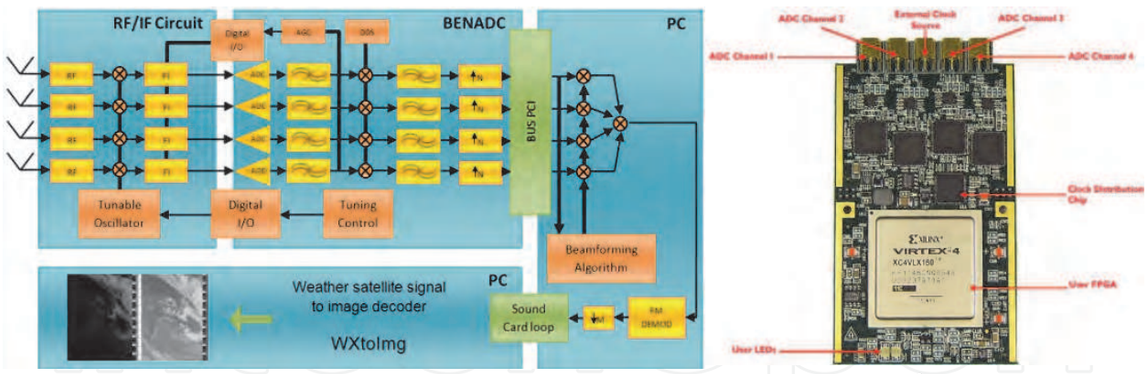


Fig. 25. a) Block diagram of the A3TB, and b) BenADC – Virtex 4-sx55.

250 Msps (Martínes et al., 2007). Digital samples are transferred to the PC where beamforming and subsequent APT demodulation of the array output are performed using C++ routines. This implementation design offers higher flexibility for testing different beamforming schemes. Finally, demodulated APR frames are sent to the WXtoImg software to show meteorological maps.

The A3TB is controlled by the PC for simulations and field trials. The graphical user interface allows presented in (Salas et al., 2008) the user to choose the beamforming algorithm and set all the parameters of the LEO satellite for tracking such as the number of antennas of the array, distance between the elements, direction of arrival and IF frequency. The C++ routine calculates the beamforming weights and plots the synthesized array factor. Subsequently, the reception of meteorological images has real time system requirements. Thus, it is necessary a data transfer from the FPGA to the C++ module to process the samples continuously, and give APT frames to the audio output of the PC. Since, the meteorological satellites often have a low baud rate, in the case of study with NOAA satellites the data transfer is made using two buffers controlled by a thread.

It is important to mention that the A3TB with SDR architecture can evaluate different beamforming algorithms and receiver schemes. The update of A3TB for larger arrays is immediate, as the basis for algorithms is independent of the number of elements in the array. The architecture of a new ground station concept to track LEO satellites based on software defined radio and antenna arraying as Test-Bed is a well proved choice to evaluate future antenna array architectures for satellite communication and benchmark features of the proposed system. As the A3TB VHF version is based on FSC scheme, the concept can be applied to a number of satellite tracing scenarios.

6. Conclusions

The performance analysis of different beamforming algorithms is an important issue in the new generation antenna array development and research. Thus, A3TB helps to analyze beamforming algorithms paving the way for testing and debugging for posteriori use in larger arrays, such as GEODA. Results obtained in real scenarios with A3TB state, for example, that spatial reference algorithms such as MPDR should be used in the absence of interferences, whereas blind algorithms are appropriate for low SNR conditions. Finally, the A3TB can also serve to validate the performance of calibration procedures.

In future work, the A3TB will deal with the system combining of full modularity with the capability of change firmwares based on the first version design of the Test-Bed, plus the flexible architecture of the current design of the Test-Bed based on VHDL, C++ and Antenna Arraying. Furthermore, the addition of more modules to increase the number of antenna array elements is evident in next generations.

7. Acknowledgment

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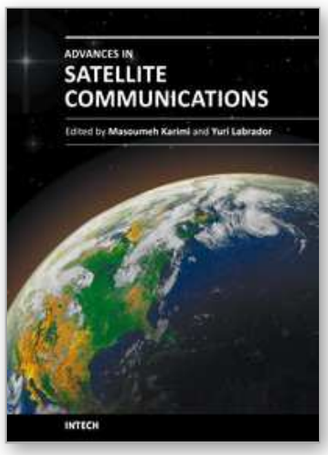
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Satellite communication systems are now a major part of most telecommunications networks as well as our everyday lives through mobile personal communication systems and broadcast television. A sound understanding of such systems is therefore important for a wide range of system designers, engineers and users. This book provides a comprehensive review of some applications that have driven this growth. It analyzes various aspects of Satellite Communications from Antenna design, Real Time applications, Quality of Service (QoS), Atmospheric effects, Hybrid Satellite-Terrestrial Networks, Sensor Networks and High Capacity Satellite Links. It is the desire of the authors that the topics selected for the book can give the reader an overview of the current trends in Satellite Systems, and also an in depth analysis of the technical aspects of each one of them.

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