Reconfigurable Satellite Payload Model based on Software Radio Technologies

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Abstract— Within this article, we look at some of the improvements which can be obtained when Software Defined Radio (SDR) technology is used in order to build satellite payloads. Afterwards, we present a SDR on-board processing model where flexibility, reconfiguration and self-configuration are considered as the prime targets. This model is explained by means of block diagrams and each one of their components is analyzed in detail. This description is mainly focused on the Intermediate Frequency process since at this stage SDR makes its strong contributions. Additionally, implementation constraints are commented and finally, further works are identified.

Index Terms— Regenerative Satellites, On-Board processing, Software Defined Radio, DSP, FPGA, Next Generation Satellites.

I. INTRODUCTION

Nowadays, one of the most important features that people, animals and systems must possess in order to guarantee their survival, is a rapid and reliable adaptation ability to become able to fit into new environments. Telecommunication systems and specially satellite systems, are not exempt from this situation. Those satellites already orbiting the Earth should permanently be technologically updated and compatible with terrestrial technologies. Nevertheless, updating a satellite which is already in orbit, represents not only a very difficult task but also a necessity considering the rapid technology growth, new service demands and certainly, the long lifetime satellites are designed for.

This is the prime reason by which technology advancement is oriented to look for an appropriate alternative to make feasible reconfiguration capabilities on satellite payloads [1] [2]. In this article, we present a model which allows satellite payloads to be reconfigured by using SDR technologies. Same way, all the advantages obtained by the usage of this technique are analyzed and explained in detail.

Software Defined Radio (SDR) is an emerging technology which allows radio systems to perform any Intermediate Frequency (IF) process using software instead of hardware. It means there are digital signal processing algorithms which perform filtering, modulation, codification or even more complex radio tasks. These algorithms are hosted on programmable logic devices (PLD) such as Field Programmable Gate Arrays (FPGA) or Digital Signal Processors (DSP), then considering these devices could be programmed and reprogrammed many times, SDR systems could change their operation mode just by changing a piece of their software [6], [7].

A SDR device replaces as much hardware with software making radio systems more flexible. As a result, radio systems could be built regardless of their final purpose and considerations such as network environment or type of services that radio systems will be used for, are not taken into consideration. In terrestrial communication systems for example, it is possible to program a SDR system in order to operate in GSM networks and by changing its software, the same device could be used in CDMA networks.

However, not all the radio devices could be replaced by algorithms, there are several radio components performing tasks such as power amplification and these processes can not be performed by PLDs but by analog active components. Nevertheless, the main idea remains the same, to put A/D and D/A converters as close as possible to the antenna system allowing radio systems to perform most of their tasks using digital signal processing. The ideal SDR system is the one where signal processing is performed at the RF stage, it is without down/up converters, but in this context, A/D and D/A converters would be required to have very high sample rates considering the frequencies that satellite systems deal with. In our approach the SDR technique has been considered to be incorporated at the IF stage.

A block diagram of a SDR receiver structure is shown on Fig 1. Notice that it is mainly made of one RF Stage which handles the signal detection and amplification, one Frequency Down Converter which translates the radio signal to the IF band and one SDR Platform which does all of the processing in order to transform an IF signal into a baseband one. In the transmission direction, an analogous process is carried out: A baseband signal is transformed into an IF one. Afterwards, it is amplified by High Power Amplifiers (HPA) and finally transmitted by the Antenna System.
Considering that radio systems based on SDR are capable of operating in different frequency bands, all the external devices as those shown in Fig. 1, must have configurable features to set up the bandwidth and central frequency in order to match the frequency band, which the SDR platform is operating in. Therefore, the SDR processor should send control messages to its surrounding radio devices, to set them up each time a change takes place. These controls are shown as dotted lines in Fig. 1.

Fig.1. Basic structure of a SDR receptor

Once the IF signal has been converted into digital, more than filtering, modulation or codification could be performed. More complex SDR transceivers can be designed to have capabilities to change its transmission parameters as a result of propagation condition estimations, available frequency bands or user demand analysis. In other words, SDR systems could be viewed as transceivers with reconfiguration and self-configuration capabilities; they can dynamically set up their parameters following particular and predefined criteria to maximize their performance, electromagnetic spectrum efficiency and quality of service. This capability brings the idea of radio systems which can be aware of their surrounding environment, and take autonomous decisions, regarding the most appropriate strategy in terms of modulation and codification schemes, beam forming, transmission power or frequency bands.

It is important to highlight that the SDR concept only applies to those tasks, which are originally performed by analog radio devices. As a consequence, all the processes carried out at baseband level do not belong to the SDR domain, since they are not radio tasks.

To summarize, SDR is seen as a promising technology to solve most of the problems related to make satellite payloads flexible and able to be updated. The next sections describe how the SDR concept could be applied to satellite systems and how it contributes to optimize satellite payload performance.

II. SOFTWARE DEFINED RADIO APPLICATIONS ON SATELLITE SYSTEMS

Consider that once geostationary satellites used for telecommunications purposes are placed in orbit, they remain for a long time with no possibility to be updated. Additionally, the process of replacing a satellite takes place only every 10 or 15 years, according to its average life time. This fact represents a lot of barriers to improve satellite services, since the current satellites systems must keep their initial features for at least 5 more years.

If it is possible to build transponders based on SDR technologies, satellites could be updated as often as needed, granting even more capabilities to them in the sense of dynamic and intelligent service area coverage and self-configuration capabilities to set up their transmission parameters as well.

In the satellite’s scenery, it is well known that multiple beams are a suitable technique to improve coverage, concentrate transmission power and perform frequency reuse. However, nowadays this possibility is limited for geostationary satellites since such beams are static in terms of number, position and size. In fact, these satellites are neither able to match new user distribution changes nor to avoid possible interference sources. By using SDR, the devices to generate multiple beams could be replaced with algorithms, which can also dynamically create as many beams as necessary with adjustable position and size. With this improvement, satellites could shape their service area according to specific user distributions or service demand by generating, adjusting and placing as many beams as necessary, wherever needed.

Also, satellite links are strongly affected by atmospheric impairments. Therefore, a margin of additional power must be considered to avoid errors or out of service periods. This margin is kept constant for every link, since it is calculated at the beginning of the link implementation. However, those impairments appear just during some periods, while the margin is considered all the time. This situation represents the unnecessary waste of transmission power since the same performance can be achieved with less transmission power when impairments do not exist. In fact, every satellite link is designed to use the same transmission strategy, regardless of instantaneous propagation conditions. Therefore, a better performance can be obtained, if those parameters were dynamically defined.

The use of SDR systems allows satellites to be aware of their current propagation conditions and to adapt their parameters both to transmit and receive the radio frequency signal in the most appropriate and efficient way. A result of making satellite links dynamically adaptable is that the power level always matches the required one, both in the transmission and reception directions. Hence, there is no room to waste transmission power and there is a guarantee that for a given propagation condition, the highest transmission rate and lowest BER would always be achieved. It is mainly due to the fact that the most appropriate transmission parameters are being used.

Notice that this adaptation is cooperatively performed by the satellite and every earth station at the same time, so synchronization between them is required. However, there is a limitation related to the time a control message takes in order to go from one of the earth stations to the satellite. Considering that at least two messages are required to perform a change (RTT = 250 ms), it is possible that fading events last
less than the message round trip time and once any adaptation is performed, the link had already been broken. This problem leads researchers to consider predictable systems in order to optimize the transmission strategy adaptation systems but the idea remains being feasible for satellite systems.

Otherwise, as well as SDR allows satellites to be aware of their surrounding environment in terms of propagation conditions, it is possible to perform a frequency scan to identify unused frequency bands to temporarily use them and hence optimize the available bandwidth using dynamic allocation. This idea makes sense since currently, satellite bandwidth and central frequency are fixed parameters for every link and during some periods, users do not use the whole capacity, so a quantity of it remains unused. By performing dynamic bandwidth allocation, each user would obtain just the required one only when needed and satellite resources could be maximized since the whole bandwidth would be uniformly available to all earth stations. The process of scanning the electromagnetic spectrum to identify frequency “holes” in order to optimize the available bandwidth, is one of the main features of the Cognitive Radio approach [3] [5] which has been claimed as a promising technology in the radio engineering field. Now, by using SDR to perform on-board processing, cognitive radio techniques become truth to satellite systems and with them, updateable and flexible satellite payloads as we shall see later on.

III. ON-BOARD PROCESSING MODEL BASED ON SDR

In classical satellite payloads, every radio task is performed by individual hardware devices which are set up before launching. Now, introducing SDR technologies, we present the satellite payload structure depicted in Fig 2. The main change occurs at the IF stage once the down conversion is performed, every signal coming from the antenna system, is digitalized to be processed by a SDR platform. Notice that the SDR platform takes over only IF stage tasks and processes such as beam switching are performed by the baseband processor [8].

In Fig. 2, one can see that our approach remains several hardware devices from the classical structure, such as the Antenna System and Radio Communication Equipment (Up/Down converters, low noise amplifiers and high power amplifiers). Nevertheless these devices, LNA, HPA and frequency converters, are far different from the old ones since they expose particular configuration features in terms of dynamic adjustment of power gain, central operation frequency and bandwidth. These devices obey the IF Processor’s commands to adapt themselves to fulfill particular configurations in both, the transmission and reception directions. This capability requires an interface which is depicted as a dashed line in the Fig 2, between the IF Processor and every radio device. This interface allows to control and to monitor the radio devices whenever a transmission/reception configuration change takes place.

The Antenna system, which must be able to generate multiple beams with size and position adjustment capabilities, consists of one feeder array which illuminates a parabolic reflector, where every feeder requires a transmission and reception chain composed by an amplifier, frequency converter and Analog/Digital converter as shown in Fig. 2. The number of chains remains undetermined, but it depends on the number of feeders disposed in the fixed array, which is at the same time defined by the required flexibility to achieve a specific number, size and position for each beam.

![Fig. 2. General transponder structure based on SDR technologies.](image)

A more detailed structure to explain the IF processor operation is exposed in Fig. 3. As shown therein, the IF Processor is made of a Beam Forming Network (BFN), a Local Controller (LC) and a variable number of Intermediate Frequency Units (IFU). The BFN main function is to create a specific number of beams with the size and orientation specified by the Local Controller (LC). Notice that for every new beam, the BFN requires an additional interface, so it dynamically adapts its number of interfaces according the number of IFUs which is equal to the number of beams. Moreover, the BFN could receive commands from the LC to change size and orientation of any beam or simply to generate or eliminate some of them.

An Intermediate Frequency Unit is a set of components which handles signals coming from each BFN output to perform carrier synchronization, modulation and codification in both the transmission and reception directions. Every IFU converts the IF signal from its respective beam into a baseband signal and vice versa. Every beam illuminating the satellite service area requires a dedicated IFU. In this context, the Local Controller creates as many IFUs as beams are required once the Central Controller (CC) has defined the number of beams. However, considering that the feeder array is fixed, the maximum number of beams remains limited by this feature.
According to the traditional approach, an IFU could be compared with a traditional transponder since its main task is to handle a signal and transmit it back to the Earth. Obviously, in this approach, baseband processing is performed before retransmissions.

The LC is mainly an interface that receives the control information from the CC and generates commands to the BFN and all the IFUs. The LC main task is to generate commands to all the IFUs and BFN, when beams must be incremented, decremented or just reorganized.

An important element associated with the IF processor structure is the one which deals with propagation channel adaptiveness. This module allows satellites to change their transmission parameters in order to use the most convenient transmission strategy when a given set of propagation conditions is identified. In this model, the adjustable transmission parameters are: transmission power, modulation (scheme and constellation size) and codification. This module generates commands to the external microwave devices as well as modulation and codification modules to adapt the transmission parameters.

The dynamic transmission parameter adjustment consists of agreements among the satellite transponder and every earth station to transmit with a particular configuration in terms of the parameters stated above. This process is possible thanks to two different systems: a signaling system and a channel estimation system. The signaling system allows both, transponder and earth station to understand each other while the process of changing transmission parameters is taking place. The channel estimation system aims to identify propagation conditions and at the same time, predicts possible fading events by means of continuous transmissions, cooperatively performed among space segment adaptiveness module and its terrestrial counterparts. Same way, predictive algorithms are considered also. All earth stations which are being illuminated by the same beam, take part in the process of identifying the most appropriate transmission configuration.

Notice that every earth station is exposed to different propagation conditions and placed at different distances from the satellite. Since for each beam there is a particular IFU configuration, there is just one single optimums transmission strategy for each beam in both downlink and uplink. Particular transmission configurations for every earth station could be considered, however, it requires as many IFU’s as earth stations are associated with the satellite. That is why this requirement demands to increase even more on-board processing capacity. In our approach, adaptiveness process defines two unique configurations for each beam. One for downlink and another for uplink and it applies to every earth station which is related with a specific beam.

Each IFU has a module which deals with Multiple Access Control (MAC) in order to share the whole satellite resources among every earth station. This module could handle any multiple access configuration, depending on the requirements of every beam. In fact, it could be different from one beam to another. A key feature of the MAC module is related to Quality of Service issues. For this purpose, a message interchange among the Local Controller and every MAC module is carried out to allow dynamic resource allocation to follow the CC commands. The CC indicates how resources must be allocated among the earth stations, following particular policies about traffic and user priorities as well as permissions and restrictions for each one.

The module which performs the interface among every IFU and the Frame Processing Component is just a buffer which allows both components to synchronize their information interchange.

The Central Controller is responsible to coordinate the interaction among IF Processor, Baseband Processor and all peripheral microwave equipment. The tasks performed by this component comprehend traffic analysis for service billing and beam configuration. This kind of analysis allows the onboard system to find out its user and service demand distribution, to determine the best beam configuration.

Fig. 3. Proposed structure of the IF Processor.
Additionally to the functions mentioned above, the Central Controller performs user management also. In other words, it keeps the user information related with status, IP configuration, restrictions and privileges to support procedures such as user terminal association, resource allocation and quality of service provision. This on board user management feature increases the satellite autonomy and reduces message interchange between satellite and control earth station, which represents high performance, less processing time and higher service level for end users.

IV. IMPLEMENTATION CONSTRAINTS

Most of the constraints to implement SDR systems are related to the processing capacity available on programmable logic devices. In this context, due to their performance, flexibility and power consumption, FPGAs have become a very attractive choice to implement SDR systems. Nevertheless, the most remarkable constraints are the frequency clock and the number of arithmetic operations per cycle the FPGA can perform. By the time being, the most powerful FPGAs is the Xilinx Virtex IV and even though those integrate up to 200.000 logic cells and use a frequency of 500MHz, models such as the one presented here are not possible to be implemented totally. Therefore, arrays of faster devices must be developed to achieve the required capacity and processing speed.

Another fact to be considered is that A/D and D/A converters define how close to the antenna system the SDR platform could be placed. It is mainly related to bandwidth issues, since the converters’ sampling rate must be at least, the one defined by Nyquist theorem in order to avoid aliasing. Therefore, processes such as frequency down/up conversion or even adaptative filtering should be considered. Additionally, the number of bits per sample (resolution) and how accurately the digital output is related to the analog input (linearity), will strongly affect the SDR platform performance also [4].

Moreover, the most important constraint to perform digital signal processing on board satellites is that PLD must tolerate the out space radiation. Consider that high radiation could impact the FPGA integrity and stored algorithms could be damaged. A very strict test plan must be performed for selecting the PLDs or/and protection systems, which will be used in this kind of implementations.

Another situation which could be considered as a constraint is the fact that traditional radio function algorithms, such as those for modulation and codification, must be optimized in order to build algorithms demanding as less resources as possible in order to reduce processing delay and allow several radio functions in the same device. However, in most cases this is a very difficult task.

V. FURTHER WORKS

Most of the work we propose to carry out about on-board processing is related to the physical layer, particularly at the IF stage. However, tasks such as IP based beam switching, Quality of Service provision, IP terminal mobility, IP multicast and TCP acceleration must be carefully considered in order to build a model to the Baseband Processor and Central Controller, which allow this kind of processing.

One consideration to design the Baseband Processor is that it must be made of two different kind of processing planes. One plane for IP processing and another one for MPLS. The IP plane is responsible for switching all the IP packets among all satellite beams, attending to IP headers and the tasks mentioned above. The MPLS plane deals with all the packets which have been labeled as MPLS traffic in some terrestrial network or with the traffic that must be labeled or unlabeled on board the satellite to pass from the IP Domain to the MPLS Domain or vice versa. Consequently, the transponder may behave either as a LSR (Label Switching Routing) or a LER (Label Edge Router) similar to those in terrestrial networks.

One more important issue is related to the reconfiguration capability. So far, we have only presented the on-board IF processing. The reconfiguration process is performed by the Central Controller but the strategy has not been defined yet and it remains being a very interesting field of research [8].

VI. CONCLUSIONS

In this article we have presented the improvements that could be achieved if SDR technologies were applied to satellite systems. In the same way, we have presented a general model to perform on-board processing using this technology. By means of block diagrams, every software component has been described. Finally, the prime implementation constraints have been identified and discussed as well.

As a final comment, we consider SDR as a promissory technology, which could contribute to improve satellite systems. However, its implementation on real satellite payloads is going to take a long time, since the current programmable logic devices do not have enough processing capacity to imibe the algorithms. Nevertheless, SDR remains being a very feasible idea for satellite systems.

ACKNOWLEDGMENT

This research is supported by the Programme AlBan, the European Union Programme of High Level Scholarships for Latin America, scholarship No. E06M101130CO.

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