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A Reconfigurable Hybrid Digital Processor for Dual Use Advanced Satellite Communication Missions

Giuseppe Tomasicchio*, Guglielmo Lulli, Gaetano Pastore

Domain Observation and Navigation Italy, Thales Alenia Space Italia, Rome, Italy

Email address:

giuseppe.tomasicchio@thalesaleniaspace.com (G. Tomasicchio), guglielmo.lulli@thalesaleniaspace.com (G. Lulli), gaetano.pastore@thalesaleniaspace.com (G. Pastore)

*Corresponding author

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Abstract: The continuous evolution of the air interfaces during the satellite lifetime, the risk of a rapid obsolescence of a payload based on on-board processing capabilities are suggesting more and more the adoption of Reconfigurable Software Radio techniques, which can be exploited to adapt the on-board processor to new waveforms, implementing software defined payload configurations; at this aim the current work proposes a new Hybrid Regenerative and Transparent Digital Processor architecture in order to improve the system flexibility and support dual-use satellite missions for civil and military applications, and finally presents some experimental results achieved in a representative end-to-end testbed demonstrator, integrating the Reconfigurable Hybrid Digital Processor.

Keywords: SatCom, Reconfigurable Software Defined, Reconfigurable Hybrid Digital Processor, Dual-Use, OBP

1. Introduction

Satellite communications constitute a vital resource for the provision of connectivity and reachability for civil and military users, particularly in critical environments and force conditions.

Disasters are unpredictable in space and time and often take place in areas with non-existing, partially damaged or completely destroyed communication infrastructures, compromising any rescue and recovery effort. Due to their wide geographical coverage - especially in geostationary orbit - satellite systems can be used for security applications in multi-beam coverage.

Dual use satellite system architectures shall be able to guarantee a seamless communication layer for different applications and support different open standard air interfaces and waveforms (e.g. DVB-RCS/RCS2, DVB-S2/X, etc).

All users, wherever they are, should be connected similarly on a common network spread over different beams, providing the possibility to route on-board traffic packets to single or multiple destination beam through a proper flexible payload processing capability. Dual-Use Communication Infrastructures today are demanding growing communication services among multi-sensors Nodes, Command and Control, reaction/actuator systems, planning, tasking with tactical and strategic information exchanges processes, which require more and more ubiquitous, reliable and adaptive means of communication. Satellite communications are critical elements for defence, security, humanitarian aid, emergency response or diplomatic communications. They are a key enabler for civil and military missions/operations in particular in remote and austere environments with little or no infrastructure. In this context in the 2015 EDA launched the GovSatCom feasibility study with the aim to prepare a future cooperative governmental satellite communication programme (2025 timeframe). The results of the study have been provided as inputs for two parallel studies (one of this awarded to the consortium led by Thales Alenia Space in Italy – TAS-I) which ESA has activated in coordination with EDA and EC with the aim to identify future mission implementation scenarios, design options and technology developments/ demonstrations necessary. In this context secure IP based communications represents the driving force enabling easy integration at technology, network and service/application levels for both Military and Civil Users. TAS in Italy in the frame of a R&D project co-funded by Italian MoD is working for analysing and consolidating key aspects relevant to the development and exploitation of novel Satellite On-board Processing technologies to support dynamic IP-based traffic communications for Military and Civil Defence operative scenarios. According to this processor architecture uplinked traffic packets are switched on-board depending from the requests extracted by the on-board demodulated signalling packets. In this way the traffic packets are switched on-board transparently. For the signalling packets processing a SW Defined approach is envisaged for adding flexibility. This is pursued with a phased approach (roadmap) envisaging the development of technological capabilities with an incremental maturity level. Three level of capabilities have been identified, on the basis of increasing complexity of: (i) identified reference scenarios, (ii) demonstration platform integrating the SATCOM component with terrestrial and space-based sensors, C2 (command and control), actuators and Homeland terrestrial Strategic Networks assets evolving from SW-In-the-Loop to HW-In-the-Loop technological readiness levels

2. Dual Use System Service and Operative Scenarios Overview

Mission scenarios analyses executed in the frame of previous works [1-4] have highlighted that international and national operational organizations are widely implementing network centric concepts in consideration of the capabilities achievable from information distribution and cooperation facilities provided by Internet services. The result is a fully meshed communication system allowing the operational actors to share needed information and to properly communicate, in order to optimize the relevant operational task results.

The most important items that characterize the network centric operations consist in ubiquitous communications and direct link from sensors to decision makers nodes and actors.

Typical examples of Security missions scenarios (including Military operations, Patrolling, Search & Rescue, Interception and capture of illegal immigrants) and information exchanges between involved entities are depicted in Figure 1 and Figure 2.

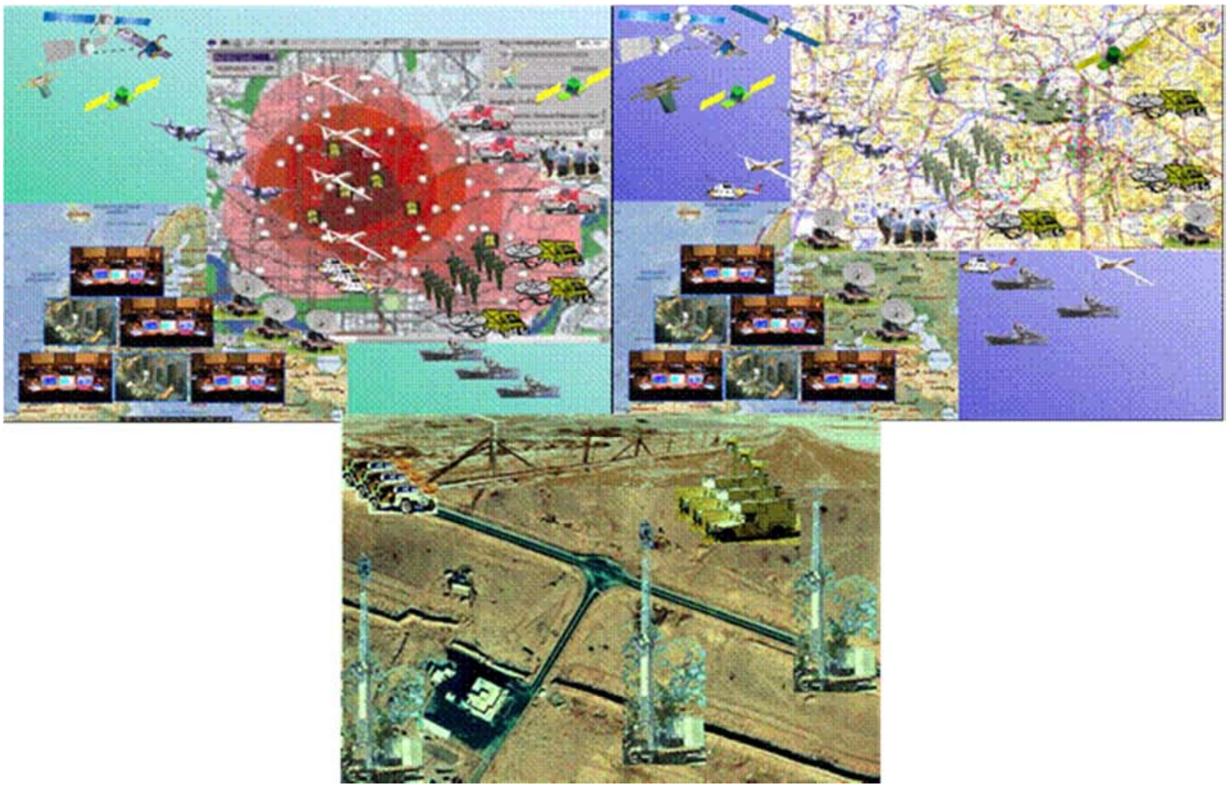

Figure 1. *Security Scenarios.*

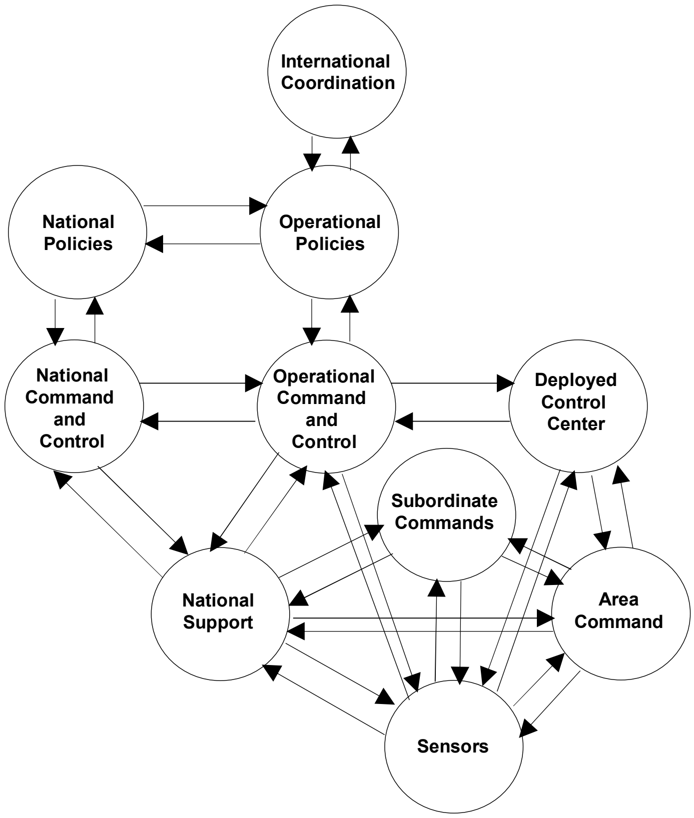

Figure 2. *Collaboration flow diagram for operational scenarios.*

An example of Information exchange requirements is provided in the following Table 1.

Table 1. *Example of Information Exchange Requirement for Security Missions.*

Data originator		ACC	Unatt. sensors	Mobile vehicle onboard sensors and crew	Aircraft & Helicopt. Onboard Sensors and crew	UAV: onboard sensors	Sat. sensors
Function originator		C2 - analysis, planning, control	Surveillance	Patrol	Patrol	Surveillance	Surveillance
	Data type	MM	M	MM	MM	I M	R
	Mode	2	1	2	2	2	1
Data transport characteristics	Distance	MF	SMF	SM	M	MF	F
	Band-width	L	L	L	L	H	H
	Importance	C	C	C	C	C	C
	Ops. Time	5	24	5	5	24	<1
Intermediate		-	-	-	-	-	Ground station
Function intermediate		-	-	-	-	-	Processing
Product dissemination characteristics	Data type	-	-	-	-	-	I
	Mode	-	-	-	-	-	1
	Distance	-	-	-	-	-	FM
	Bandwidth	-	-	-	-	-	H
	Importance	-	-	-	-	-	N
	Ops. time	-	-	-	-	-	<1
Product receptor		NCC	ACC	ACC	ACC	ACC	ACC
Function receptor		C2 - planning	C2 - analysis	C2 - planning	C2 - planning	C2 - analysis, planning, control	C2 - analysis

Notes: A dash in the intermediate column means that there is no intermediate node and the data flows directly from the data generator to the product receptor.

Parameter values are:

1. Data type:
   a. Raw data (R), can be interpreted as data directly produced by the sensor;

b. Images (I), means a product created from the raw sensor data;
c. Messages (M), like for instance communications or target coordinates.

2. Mode:
   a. One-way (1), data flows from a single originator to a single receptor;
   b. Two-way (2), data flows from a single originator to a single receptor and vice versa;
   c. Multi-casting (M), data flows from single originator to multiple receptors.
3. Distance between nodes that have to be connected:
   a. Short (S), interpreted as 40-50 Km, within range of VHF radio
   b. Medium (M), means 100-300 Km, within range of MF radio;
   c. Far (F) beyond 300 Km, outside range of radio.
4. Bandwidth in bits per second (bps) typically required for transporting the data:
   a. Low (L), can be interpreted as below 10 kbps, e.g. used for digital messages;
   b. Medium (M), means of the order of 64 kbps, e.g. used for direct voice communication;
   c. High (H), means of the order of 1Mbps as used for transferring images.
5. Importance of the function to stay operational:
   a. Low (L), means communication may be interrupted during operations;
   b. Normal (N), means communication may be interrupted occasionally during operations;
   c. Critical (C), means communication may never be interrupted during operations.
6. Operation time: i.e. the time in hours per day that the function has to be operational.

3. Software Defined Payload (SDP) Architectures

Security missions (both Civil and Military) require the capability to rapidly react to various scenarios. Reconfigurable and flexible satellite payloads design represent a candidate solution to improve system responsiveness with respect to statically configured payloads for multiple different communications scenarios.

Software Defined Radio (SDR) technologies represents a first step forward for new satellite payload design concepts where some or all of the baseband or RF signal processing is accomplished through the use of digital signal processing (DSP) software and can be modified post manufacturing, [5-6]. This approach enables the exploitation of flexible solutions, based on Digital Signal Processing (DSP) algorithms, removes the obsolescence problem for payloads based on processing capabilities, reduces cost and risks for various missions, but requires technological advances on Key enabling technologies (KET), such as programmable space qualified platforms based on a set of programmable processors and Field Programmable Gate Arrays (FPGAs), etc [7-8].

In Figure 3 a generic SDP architecture for a multi-beam satellite mission is presented where the RX and TX front-ends are digitally processed in parallel from signal processing sections and a digital switching stage.

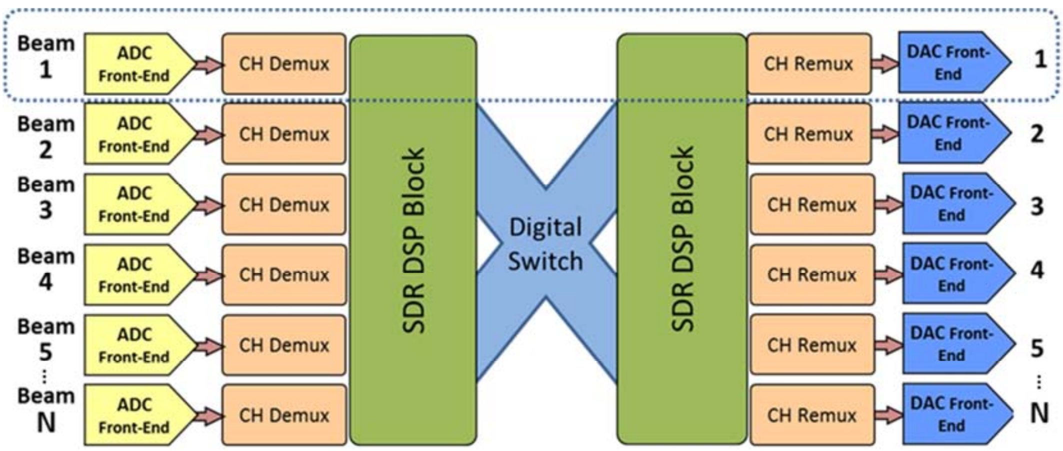

Figure 3. *Generic SDP Architecture Functional Diagram.*

In general it is worthwhile to note that not all processing sections in a satellite payload do have the same requirements in terms of processing power, re-configurability and probability of modifications induced by new services or demand types. This way, ASICs can be used in the most exigent sections in terms of processing speed or for the most static ones from one mission to another. Re-programmable devices shall be included in the chain for those activities that depend on the final customer needs and may be subject of evolutions during the satellite's life time. In this context, integrated architectures with mixed technologies approach selecting the most suitable key technology for each one of the processor components/sections, seem to be the best solution for long-term flight products [9-11].

4. SDP and Mission Reconfigurability

In order to support mission re-configurability/flexibility a new reconfigurable on board processor payload concept has been developed by TAS-I in the frame of some R&D projects, [12-14]. This payload constitutes an example of SDP system implementing payload mission re-configurability capabilities. The system is based on a Reconfigurable Hybrid Regenerative and Processed satellite payload and provides unicast and multicast/broadcast single hop mesh and star intra-beam and inter-beam communications (with cross-banding capabilities) based on IP protocol. The Digital Payload system supports prioritization policies on the time-varying traffic flows and dynamic resource assignment in order to provide different levels of QoS (dynamic bandwidth allocation capability) to users accessing on different coverage area and different frequency bands (cross-banding).

In Figure 4 it is depicted the architectural layout for the overall satellite system. This architecture represents a candidate solution to support multi-beam mesh services for military users on governmental side as well as highly demanding professionals or for rural telephony services, on commercial side. With this type of architecture the OBP complexity is minimized in order to lower as much as possible the impact in the whole satellite budget.

The routing in the space concept is based on dynamic data bursts switching. This means that data bursts transmitted on the uplink traffic channels are not processed (demodulated and decoded) on board but simply switched (as digital samples). The routing information (e.g: destination downlink(s)) are converted within signaling channels containing capacity requests (i.e. required bandwidth to transmit an amount of traffic and the associated routing information).

The main functional entities of the reconfigurable OBP processor are listed in the following:

1. Analogue front end and associated ADC and DAC converters;
2. The channelization function performing fine digital filtering of sub-channels. Sub-channels bandwidth is variable and programmable by ground commands.
3. Mo/Demodulation and Co/Decoding units for signalling channels (e.g. DVB-RCS/DVBS2 compliant even though reconfigurable via SDR to support future evolutions);
4. OBP switch performing a full connectivity routing at sub-channel level between the input and output ports. Main characteristics of the switch are:
   a. Frequency, Spatial and Time switching;
   b. Non-blocking switching capabilities;
   c. Broadcast and multicast capability.
5. OBP Controller unit implementing the following functions:
   a. Traffic Resource Management: which mainly consists in the processing of the requests from Terminals;
   b. computation of a terminal burst time plan, to share the up-link resources among all the satellite terminals which require access to the satellite system.

The resource assignment process takes care of the QoS of the transmitted data streams as well as their destination;

   c. configuration of the Switch Unit on the basis of the results of the resource assignment process.

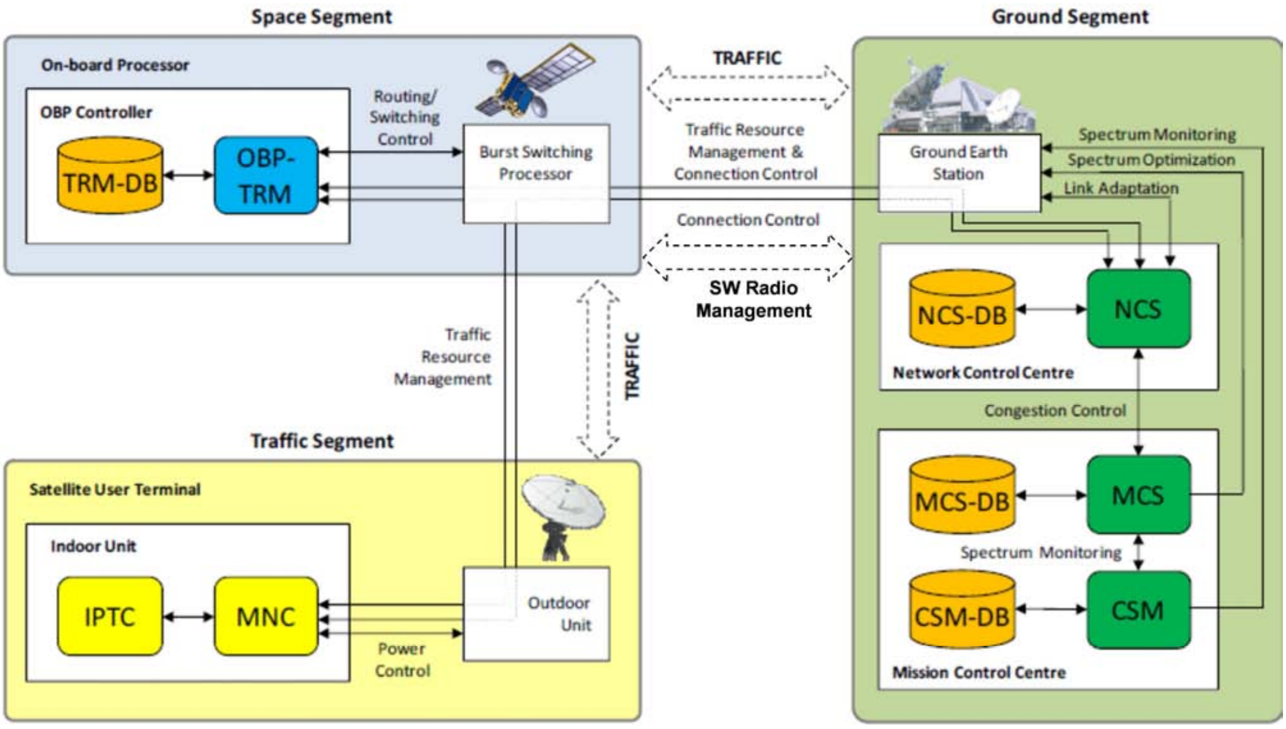

Figure 4. *Example of SDP based Satellite System Architecture.*

The possible solution and advantages of implementing these functions in SR technologies has been already highlighted in paragraph 2.

5. Architecture of the Test Bed and Achieved Results

The Hybrid Regenerative and Translucent Digital Processor breadboard device has been integrated in the frame of the TAS-I Concurrent Design Verification Facility (CDVF) which, according to the architectural layout in Figure 5, has been adapted and specifically configured to host the processor breadboard with the aim to implement the E2E validation campaign addressing several different operational scenarios.

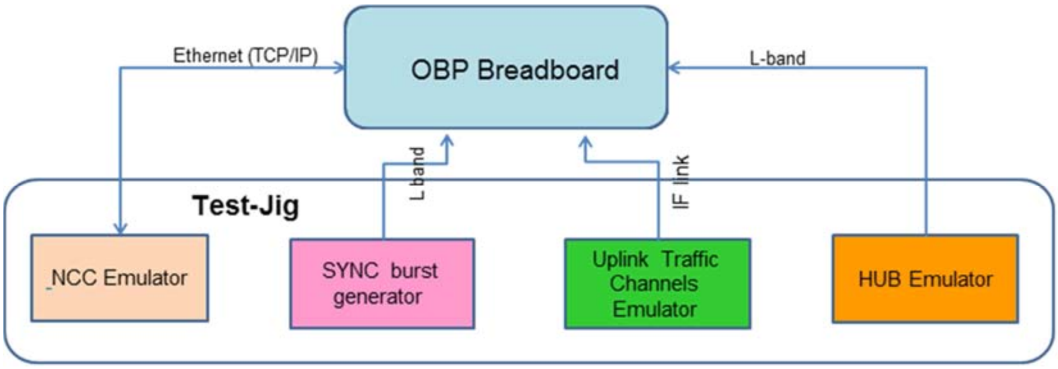

Figure 5. *E2E Validation campaign Test bed architecture.*

The test bed components which have been exploited for the validation campaign through test bed test are:

1. NCC emulator: is a SW module developed by

TAS-I to insert / modify configuration scenarios and other control parameters to be loaded from the NCC to the OBP breadboard database and also to monitor some breadboard activities.

2. HUB Emulator: used to generate DVB-RCS

signaling for the Forward Link in order to stimulate the OBP processor functions related to the synchronization, the DVB signal handling / management and the overall downlink multiplex generation.

3. SYNC Burst Generator: used to generate Capacity Requests (CR) aimed to stimulate OBP TRM.
4. Uplink Traffic channels emulator: used to emulate physical channel impairments on uplink and downlink connections.

Besides the above elements several analysis tools and ancillary components have been used in the best bed such as Oscilloscopes, Vector Signal Generators, Spectrum Analyzers, BER Meters, SCPC Modulators and Demodulators, Forward and Return Link DVB-RCS Protocol Analyzer (FRLA), Reference Time and Frequency generators.

Several connectivity topologies have been tested in order to validate the following operational scenarios:

a. Meshed Traffic exchange of real traffic between DVBS2-RCS Emulated Meshed Terminal through the OBP.
b. Hybrid Transparent & Switched Traffic exchange with DVB HUB Emulator and the OBP sustaining Terminals in the DVBS2-RCS network and concurrently SCPC communications in hybrid transparent and switched traffic exchanging.
c. HUB and Spoke for Backward Compatibility with DVB HUB Emulator sustaining Terminals according to a transparent scenario.

The abovementioned scenario will allow also to perform and validate connections involved intra-beam and inter-beam communications as depicted in

Figure 6.

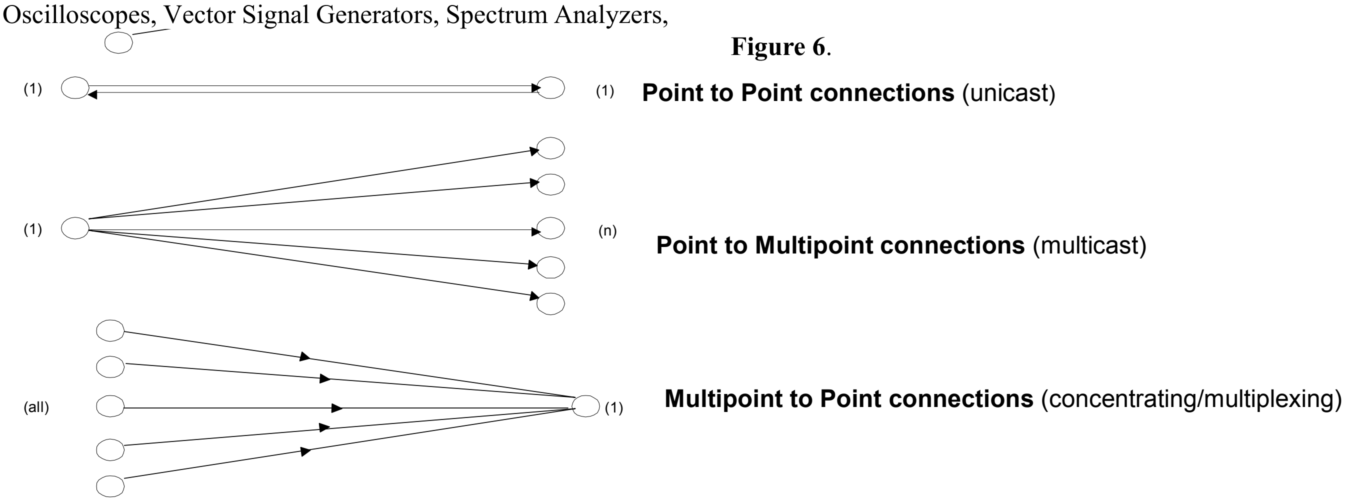

Figure 6. *Connections topologies.*

In the following some results gathered in the frame of the E2E validation campaign are reported.

The considered reference case is the Hybrid Transparent & Switched Traffic scenario, see Figure 7, implementing:

a. a point to multipoint connection involving two destination beams for TDMA traffic exchange;
b. a point to point connection for SCPC traffic exchange.

The following Figure 7 shows the Testbed configuration suitable to provide support for the Verification Scenarios, devoted to extended test of the OBP, aiming to verify the simultaneous compatibility of a hybrid configuration of a Burst Switching Processor (BSP) on which a switched TDMA DVB-RCS traffic is concurrent, and not penalized, by an existing SCPC static channel configuration. The Test layout in the picture shows an additional block comprising a SCPC Terminal with associated BER meter, that can be considered as standard instruments belonging to the pool to be addressed each time it is requested by tests needs.

The Figures 8 and 9 shows the TDMA slots occupancy on the downlink carrier and the performances in terms of timing and frequency offset with respect to frame configuration as the result of the burst switching process performed by the processor breadboard. The Figures show the measured performances on the downlink TDMA signals at data packet level and in particular that no data corruption is introduced by the processor breadboard. The Figure 10 and Figure 11 provide the spectrograms relevant to the downlink signals (TDMA and SCPC) on the two involved beams (beam 1 and beam 2) and in particular show that the SCPC signal is switched without degradations. The Modulation Error Rate (MER) and Error Vector Magnitude (EVM) measurements have been used to evaluate if signals modulation is affected by the processor. The results show symmetric constellation and no Phase Modulation (PM) or Amplitude Modulation (AM) degradations. When the average Phase Err. (in degrees) is larger than the average Mag. Err. (in percent) by a factor of about five or more, this indicates that some sort of unwanted phase modulation is the dominant error mode. AM is normally evidenced by magnitude errors that are significantly larger than the phase angle errors. It is worthwhile to note that in these figures, the spectrum representation of the signal does not show non-linearity effects such as spectral regrowth.

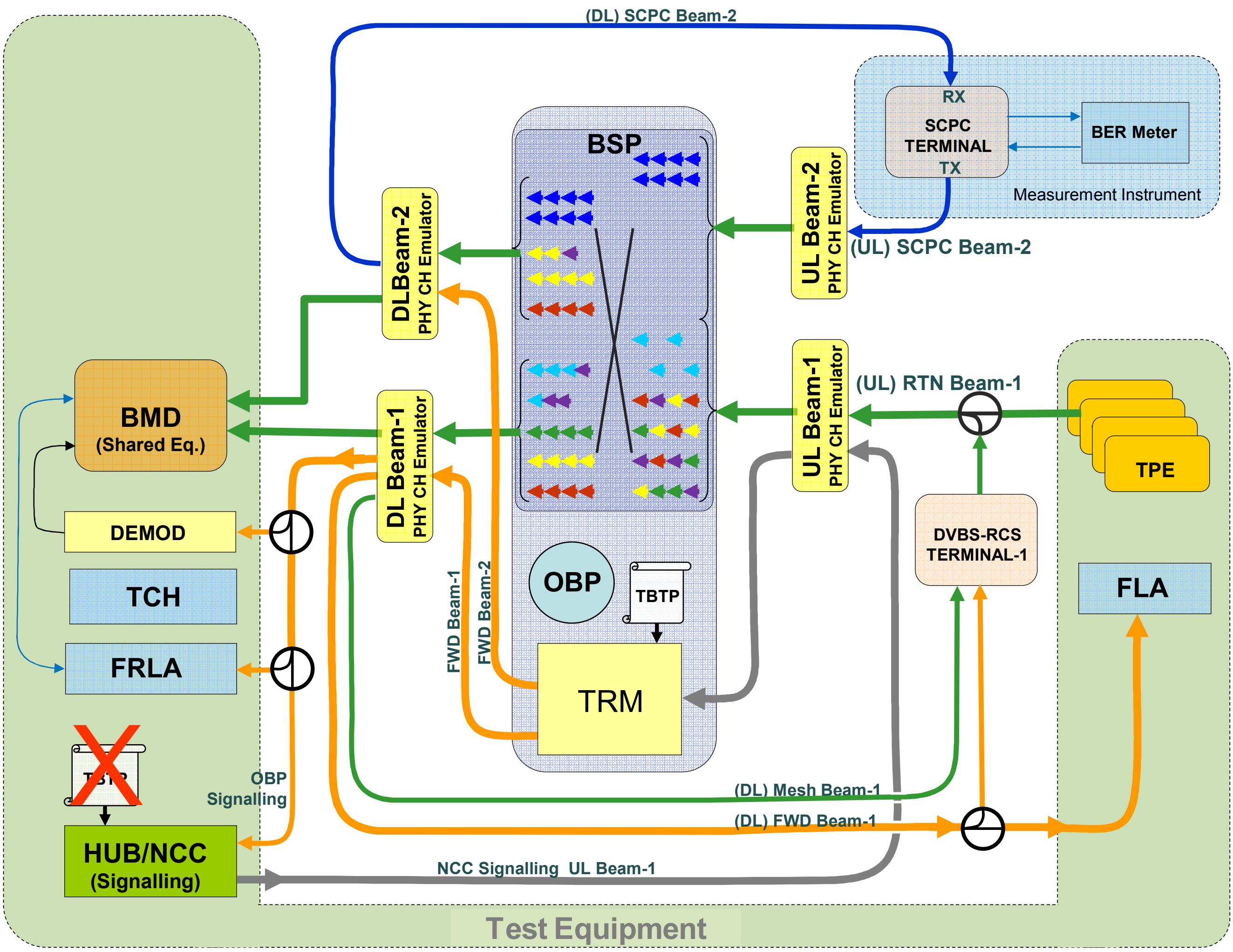

Figure 7. Testbed configuration for Hybrid Digital Transparent and Switched traffic Testing.

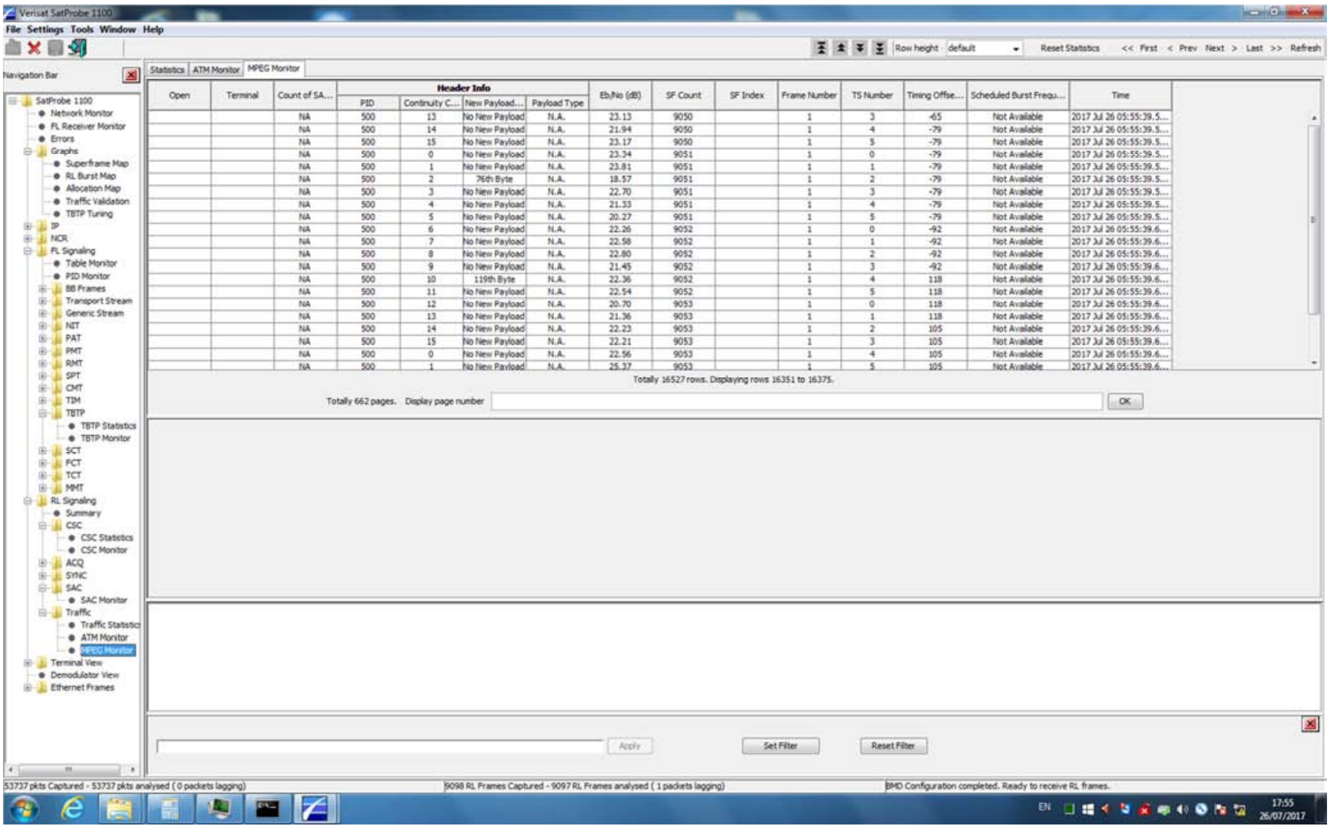

Figure 8. *Hybrid Transparent & Switched Traffic Scenario - received downlink TDMA traffic data packet performances.*

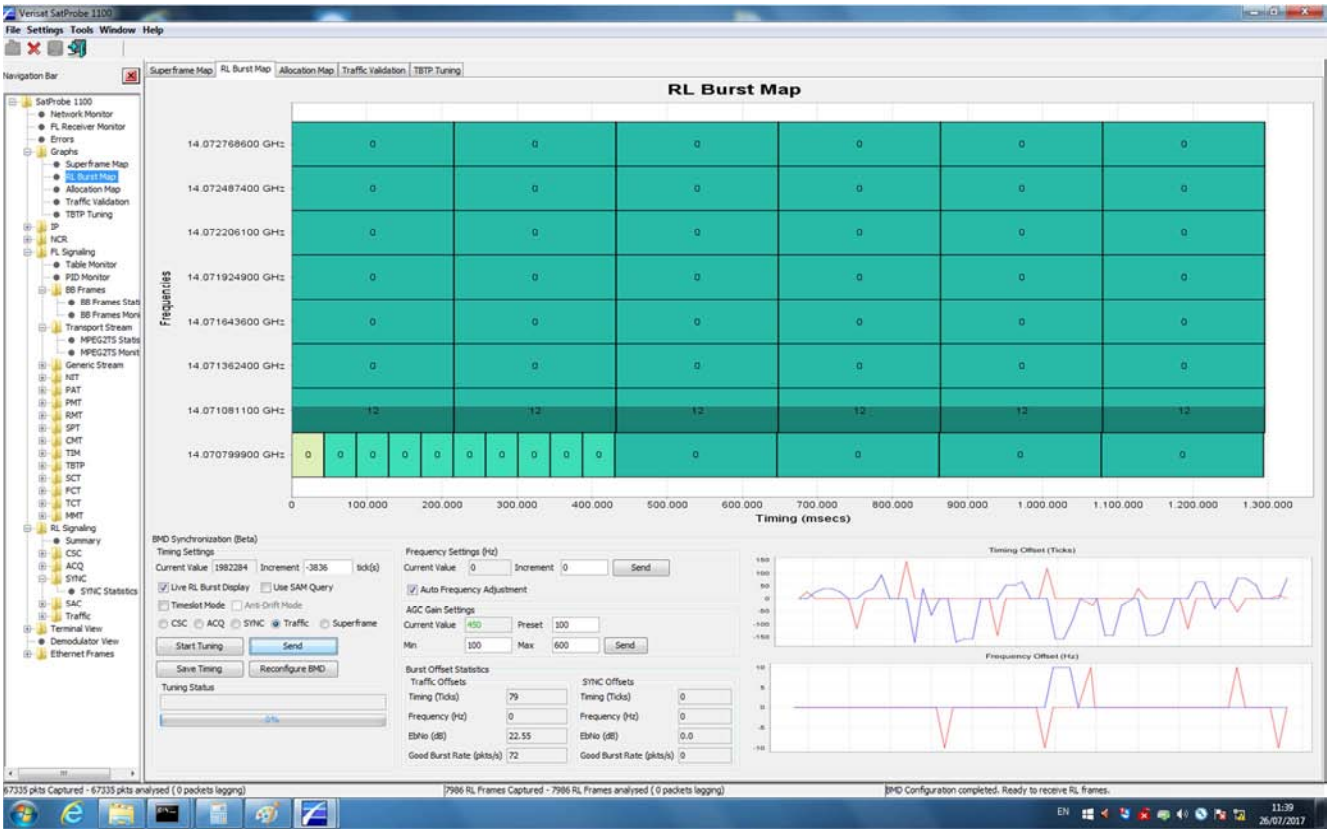

Figure 9. *Hybrid Transparent & Switched Traffic Scenario - downlink traffic burst map.*

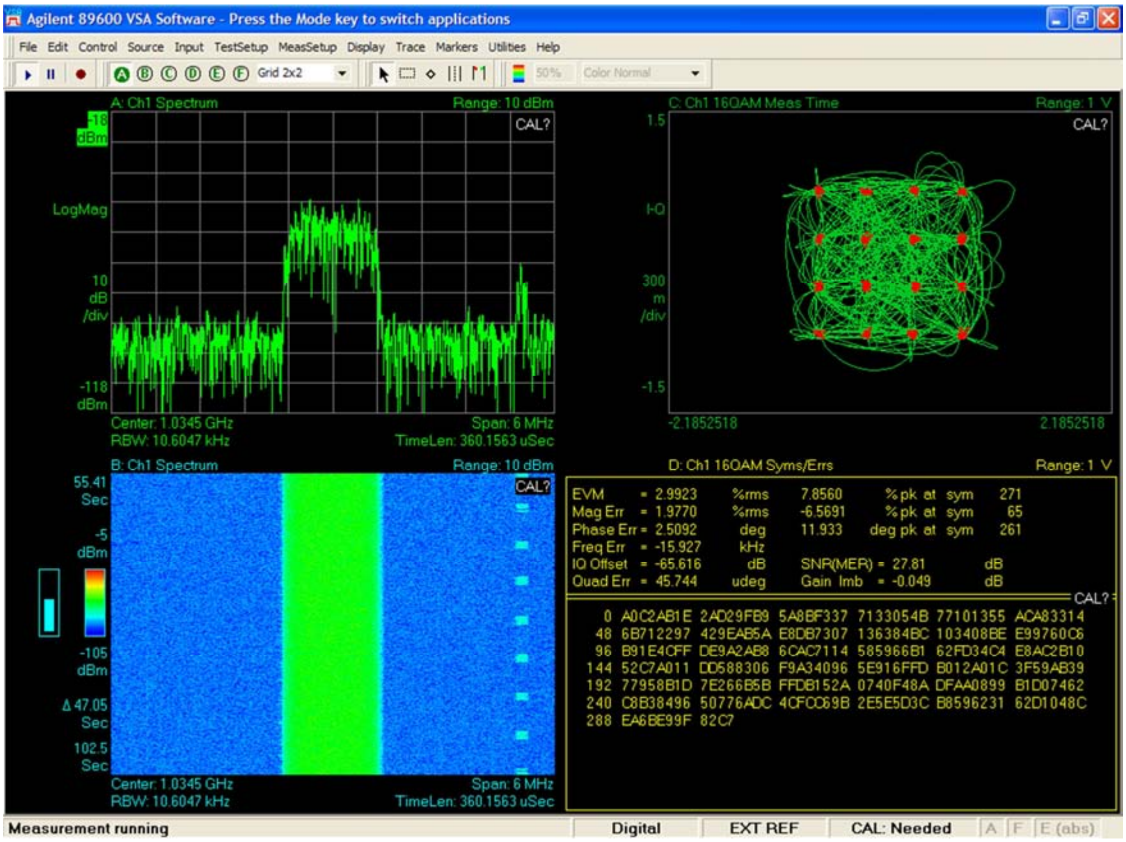

Figure 10. *Hybrid Transparent & Switched Traffic Scenario - spectrogram relevant to the downlink on Beam 1 of one unicast connection supporting SCPC traffic exchange from Beam 1 to Beam 1 and one multicast connection supporting TDMA traffic exchange from Beam 1 to Beam 1 and Beam 2.*

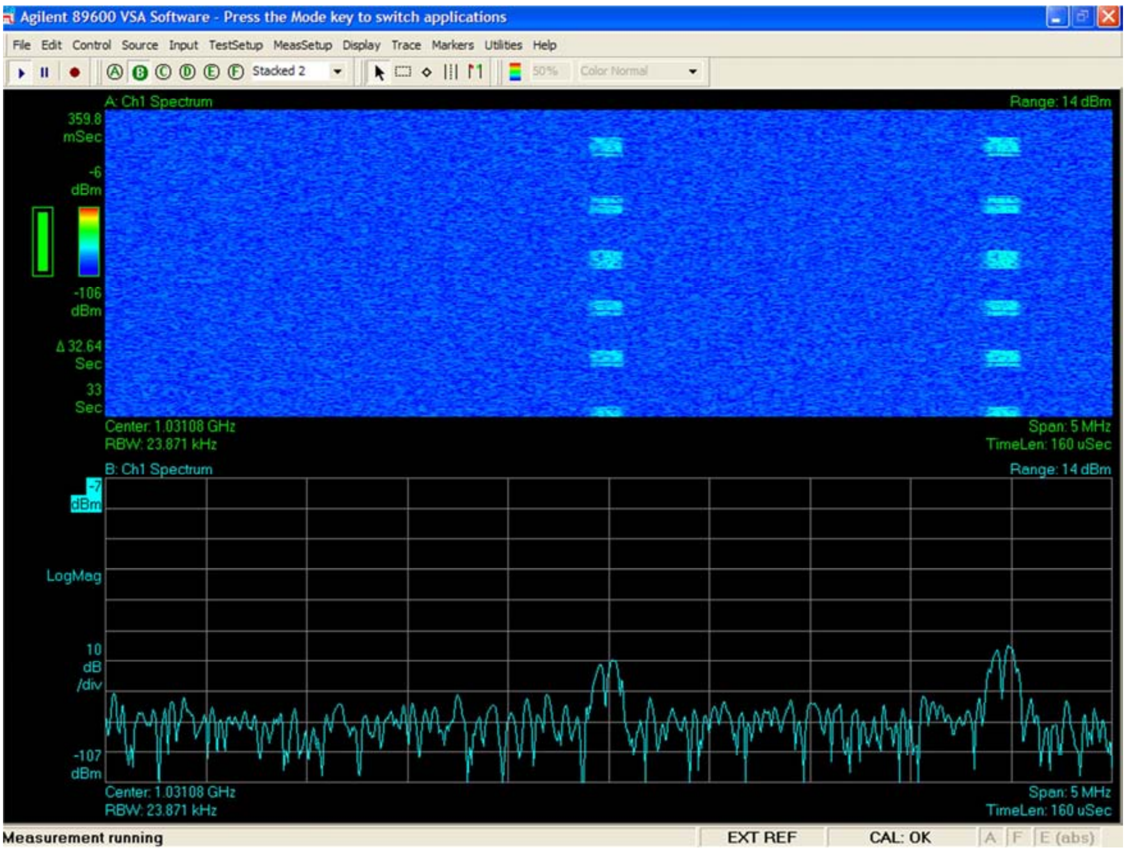

Figure 11. *Hybrid Transparent & Switched Traffic Scenario - spectrogram relevant to the downlink on Beam 2 of one multicast connection supporting TDMA traffic exchange from Beam 1 to Beam 1 and Beam 2.*

Finally, it is worthwhile to note that the Reconfigurable Hybrid Digital Processor has been also validated in extended Hybrid Transparent & Switched Traffic scenarios, where, as depicted in Figure 12, the system is able to guarantee the support, as in a full transparent way, of the standard Hub & Spoke traffic exchange for a typical a DVB-RCS sub-network, where the Terminal Burst Time Plan (TBTP) is normally sent to the terminals population by the Hub itself.

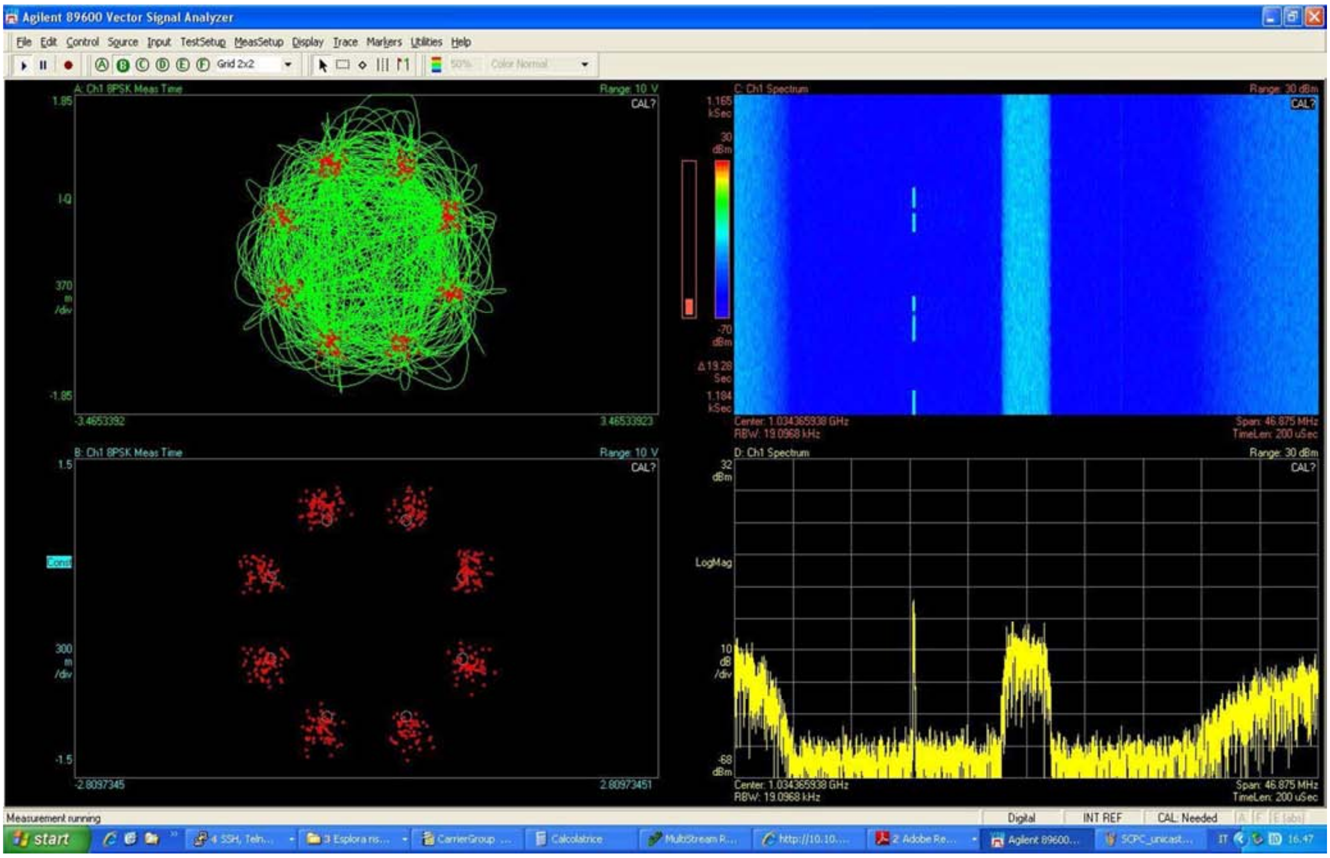

Figure 12. *Hub & Spoke transparent Traffic Scenario - spectrogram relevant to the Hub downlink and TDMA terminal traffic on the same Beam.*

6. Conclusions

To support Dual-Use Satellite Systems missions demanding for flexibility, re-configurability and rapid to react system capabilities, a SW Defined Payload (SDP) approach has been presented in this paper.

Mission scenarios and related information exchange requirements in different coverage area of interest make attractive SDP solutions for the today space community. A preliminary analysis of SDP architectures and design constraints have been addressed using alternatives key technologies to design a scalable and reconfigurable HW architecture based on different payload components (mixed technologies approach).

In this work the basic concepts of the on-flight re-configurability for an On-Board Processor (OBP) of next generation satellite payloads have also been described.

Finally, a representative end-to-end testbed demonstrator, integrating the Reconfigurable Hybrid Digital Processor (RHDP), have been described together with some relevant experimental results achieved this testbed environment. The results of the test campaign have validated the capabilities of the processor breadboard concept to support dual military and civil mission scenarios and satisfy with advanced flexibility the desired information exchange requirements. On the bases of the promising results achieved ([15], patent pending N. PCT/EP2017/058471), the next steps will be focused on increasing the technology readiness level of both the RHDP and also at system level of the overall end to end testbed components in order to prepare a suitable consolidation of the processor technology readiness level.

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