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Beneficiary Number	Beneficiary Name	Beneficiary Short Name	Country
1 (Coordinator)	TTI Norte, S.L.	TTI	Spain
2	Airbus Defense and Space SAS	AIRBUS	France
3	Universita degli Studi di Roma Tor Vergata	UNITOV	Italy
4	Fundación Tecnalia Research & Innovation	TECNALIA	Spain
5	OMMIC SAS	OMMIC	France

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Abbreviations and Definitions

Acronym	Description
3D	Three Dimensional
4G	Fourth Generation
5G	Fifth Generation
A	Ampere
AC	Alternate Current
AD	Applicable Document
ADS	Advanced Design System
ALC	Automatic Level Control
AMR	Absolute Maximum Rating
AWR	Advancing the Wireless Revolution
BO	Back-Off
BSS	Broadcasting-Satellite Service
BUC	Block Up Converter
BW	Bandwidth
C	Celsius degree
CAD	Computer Aided Design
CAN	Controller Area Network
CAPEX	Capital Expenditures
CFRP	Carbon Fiber Reinforced Plastic
CM	Control Module
COTS	Commercial Off-The-Shelf
CP	Contingency Plan
CW	Continuous Wave
dB	deciBel
dBc	decibel with respect to carrier
DBS	Direct Broadcast Satellite
dBm	decibel with respect to milliwatt
dBW	decibel with respect to watt
DC	Direct Current
DCL	Declared Component List
DCMM	Declared Material and Mechanical part

DDD	Deep Dielectric Discharge
DDB	Development Baseline
DLV	Deliverable
DML	Declared Material List
DMPL	Declared Mechanical Parts List
DOA	Description of Action
DPL	Declared Process List
DRC	Design Rule Checking
EAR	Export Administration Regulations
EC	European Commission
ECSS	European Cooperation for Space Standardization
EEE	Electrical, Electronic and Electromechanical
EIRP	Equivalent Isotropically Radiated Power
eGaN	Enhancement-mode Gallium Nitride
EM	Engineering Model
EMC	ElectroMagnetic Compatibility
EMI	ElectroMagnetic Interference
EPC	Electrical Power Conditioning
EQM	Engineering Qualification Model
ESD	ElectroStatic Discharge
EU	European Union
FB	Full Bridge
FCL	Foldback Control Loop
FGM	Fixed Gain Mode
FET	Field Effect Transistor
FIT	Failure in Time
FM	Flight Model
FMECA	Failure Mode, Effects and Criticality Analysis
FT	Feed Through
g	gram
GA	General Assembly
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GBPS	GigaBit Per Second

GCU	Gain Control Unit
GD	Group Delay
GEO	Geostationary Earth Orbit
GHz	Giga Hertz
GSE	Ground Support Equipment
HB	Half Bridge
HEMT	High Electron Mobility Transistor
HPA	High Power Amplifier
HPM	High Power Module
HPS	High Power Section
HTS	High Throughput satellite
IBO	Input Back Off
ICD	Interface Control Document
ICT	Information and Communication Technology
IDQ	Quiescent Drain Current
IEEE	Institute of Electrical and Electronic Engineers
IM	Innovation Manager
IM3	Third-order Intermodulation
IMD	Intermodulation Distortion
IPR	Industrial Property Rights
IRL	Input Return Losses
IOT	Internet Off Things
ISOL	Isolator
ITAR	International Traffic in Arms Regulations
KHz	KiloHertz
KPI	Key Performance Indicator
LCL	Latch Current Limiter
LDO	Low Dropout
LIN	Linearizer
LNA	Low Noise Amplifier
LSI	Large Signal Intergrator
mA	milliAmpere
MAG	Maximum Available Gain
MC	Matrix Command

M&C	Monitor and Control
MCU	Microcontroller Unit
MEC	Mechanical and Thermal System
Mm	millimeter
MMIC	Monolithic Microwave Integrated Circuits
MP	Mitigation Plan
MPIU	Master Power Interface Unit
MPM	Medium Power Module
mS	Milli Siemens
MS	Milestone
msec	millisecond
MTTF	Mean Time To Failure
MWO	Microwave Office
N.A.	Not Applicable
NC	Non-Conformance
nm	nanometer
NOP	Nominal Operating Point
NPR	Noise Power Ratio
OBC	On Board Computer
OBO	Output Back Off
OPEX	Operational Expenditure
ORL	Output Return Losses
PA	Power Amplifier
PAM	Product Assurance Manager
PAP	Product Assurance Plan
PAE	Power Added Efficiency
PC	Project Coordinator
PCB	Printed Circuit Board
PDK	Process Design Kit
PHEMT	Pseudomorphic High electron mobility transistor
PMT	Project Management Team
PO	Project Officer
PT	Product Tree
Psat	Power saturated

PSU	Power Supply Unit
PWM	Pulse Width Modulator
QML	Qualified Material List
RC	Radial Combiner
RD	Reference Document
R&D	Research and Development
RF	Radiofrequency
RFT	Radio Frequency Tray
RMS	Root Mean Square
S/S	Subsystem
SiC	Silicon Carbide
SMA	SubMiniature version A
SME	Small and Medium Enterprises
SoA	State of the Art
SPC	Spatial Power Combiner
SSPA	Solid State Power Amplifier
SSPC	Solid State Power Controller
SW-LP	Single Waveguide-Longitudinal Probes
TBD	To Be Defined
TC	Telecommand
TE	Transverse Electric
TEMA	Temperature Analog Telemetry
TEM	Transverse Electromagnetic
TM	Telemetry
TRL	Technology Readiness Level
TWTA	Traveling-wave Tube Amplifier
µm	micrometer
V	Volt
VHLC	Very High-Level Command
VHTS	Very High Throughput Satellite
VM	Verification Matrix
VVA	Voltage Variable Attenuator
W	Watt
WP	Work Package

1. Summary for Publication

1.1. Summary of the Context and Overall Objectives of the Project

FLEXGAN is a European research project co-funded from EU H2020 programme funds. The project Ka-band GaN-based SSPA for FLEXible payloads and multicarrier operation for 5G satellite concept (FLEXGAN) aims at designing, developing and testing, in a representative space environment (TRL5), a low cost high power and efficient Ka-band Gallium Nitride (GaN) Solid State Power Amplifier (SSPA) with RF output power varying capability (flexible SSPA), with high innovative & low loss recombination schemes and with the ability to operate in multicarrier operation mode for highly flexible payloads for 5G satellite applications. The operational frequency band is 17.3-20.2 GHz, and the objective output power is 125 W CW.

5G demand requires the deployment of very High Throughput Satellites (vHTS) than can satisfy the expected needs implying a growth opportunity for GEO satellites. This kind of spacecraft offers high capacity, large number of users and communication volumes (1 Terabit/s per satellite), with lower cost per GBPS, increasing the flexibility since the satellite capacity is allocated where it is needed. Future vHTS satellites will make use of Ka/Q/V gateways where the forward payload link will operate in K-band. Traditionally, demand for power at high frequencies has resulted in Travelling Wave Tube Amplifiers (TWTAs) as the logical amplifier of choice; this is due to the fact that traditional Solid State Power Amplifier (SSPA) technology was unavailable at similar performance levels. However, technological advancements such as linearization, miniaturisation, and the use of different materials such as Gallium Nitride (GaN), have levelled the playing field for SSPAs. GaN SSPAs employ more units with less power leading to a better agility, less redundancy, generic and reconfigurable payloads.

High efficiency GaN SSPAs can replace TWTAs in high power and high frequency payload applications if technology at MMIC level is able to provide the required RF power in Ka band with the efficiency that the system needs. Furthermore, in space applications the size and weight are also limited resources which directly affects the satellite launch cost.

The impact of GaN technology in space-borne units is now a priority concern due to the different applications in which it can be used. There are some initiatives to develop GaN MMICs and low power GaN based HPAs. However, it has not identified any project or development in Ka-band for the development of high power GaN based SSPAs due to the challenge in the design of the efficient combination of several GaN devices at Ka-band frequencies whereas the size and weight is kept as low as possible. The main technology innovations that FLEXGAN brings are:

1. Bring known terrestrial technologies by TTI to space
2. SSPA able to provide the required output power maximising the power added efficiency to compensate the downlink fading losses
3. SSPA able to transmit in multicarrier mode w/o memory effect
4. Implementation of highly innovative linearization techniques
5. Use of lightweight composite structures to decrease the weight of the overall SSPA
6. Employment of low loss combination technique.
7. Design, develop and test of a Ka-band HPA Monolithic Microwave Integrated Circuit (MMIC) based on D01GH technology from OMMIC to have a 100% European SSPA

FLEXGAN will develop a high power GaN based SSPA with the design challenge of the efficient combination of several GaN devices at Ka-band whereas the size, weight and power consumption are kept as low as possible.

There are several important efforts in Europe focused on demonstrating the capabilities of GaN technology applied to HPA for space segment. Despite of the promising results, there is still some uncertainty in the aerospace market to introduce a new technology by replacement of another (TWTAs) that has demonstrated its validity during years. FLEXGAN will allow reinforcing and corroborating the use of GaN technology for space applications.

FLEXGAN Consortium members have a wide experience in the design of Ka-band GaN based SSPAs for satellite communications in the ground segment. However, a scenario for space hardware is quite different and more challenging from ground hardware. Some of the critical challenges are: the on-board DC power generation, the thermal management, the multipaction and corona effects due to vacuum operation, the ionizing radiations, the availability of space qualified component, the reliability guidelines, etc. Therefore, this project will bring known terrestrial technologies to space.

Apart from the innovations above mentioned, FLEXGAN also will:

- Allow to reinforce and corroborate the use of GaN technology for space applications.
- Bring known terrestrial technologies to space.
- Create new business opportunities around space market.
- Stimulate the integration of space into European society and bring benefits to European citizens:
- Provide 5G satellite connectivity and resilience:
    - Wide connectivity: anywhere/anytime
    - Cost per bit reduction
    - Security union
    - Reduction of OPEX and CAPEX in the 5G radio networks
- Promote jobs creation: qualified employment
- Contribute to European research and technology ecosystem
- Participate in climate resilient future: FLEXGAN as a “Green technology”

Considering that this equipment is a category D unit according to the definition in ECSS standards, certain design margin is included in the RF power capability with respect to values required by the satellite. In a first phase of the project it will be developed:

- High power & high efficiency combination techniques
- A complete EM of an SSPA (EPC, RFT, thermal & control) based on non-EU technology (a 10 W MMIC from Qorvo will be used for the first EM development (model TGA4548)) and on high efficiency combination techniques. This SSPA will be functionally and electrically tested, as well as temperature tests will be accomplished.
- A MMIC based on GaN EU technology with 10W of output power, complying space de-ratings and with similar requirements in terms of output power as the 10W HPA MMIC from Qorvo (US), for the replacing of non-EU MMIC.

In a second phase of the project, the developed EM will be upgraded by replacing the GaN power module based on a non-EU technology with the EU-MMIC designed and realized with OMMIC technology. The EM developed in the phase 1 of the project will be used to benchmark the results obtained in phase 2. This second EU-SSPA will be functionally and electrically tested, as well, and submitted to environmental and mechanical tests in such a way that the developed amplifier will be tested and characterized in a relevant environment (TRL 5).

The concrete objective of FLEXGAN are:

- Objective 1: Establish specific requirements for the design and development of a GaN based SSPA suitable to operate in satellite networks operating in Ka-band for future 5G connectivity.
- Objective 2: Design, develop and test an EM SSPA based on non-EU technology. The idea is to have in a first phase a SSPA that could be fully characterised and useful to demonstrate key challenging

aspects of the design of an EM SSPA that is fully representative of a FM configuration. In this way as output of objective 2 aspects such as multipaction, corona effects, thermal dissipation, output power flexibility and high efficiency combination at Ka-band will be fully designed and tested in the phase 1 of the project.

- Objective 3: Design and test a MMIC based on European D01GH GaN technology from OMMIC.
- Objective 4: Upgrade the EM SSPA (objective 2) using the MMICs from OMMIC (objective 3) and perform environmental tests in order to have at the end of the activity a TRL5 SSPA. All the research findings and results of FLEXGAN that don't compromise the future exploitation activities will be disseminated and communicated to the scientific and industrial community as well as to the general audience.

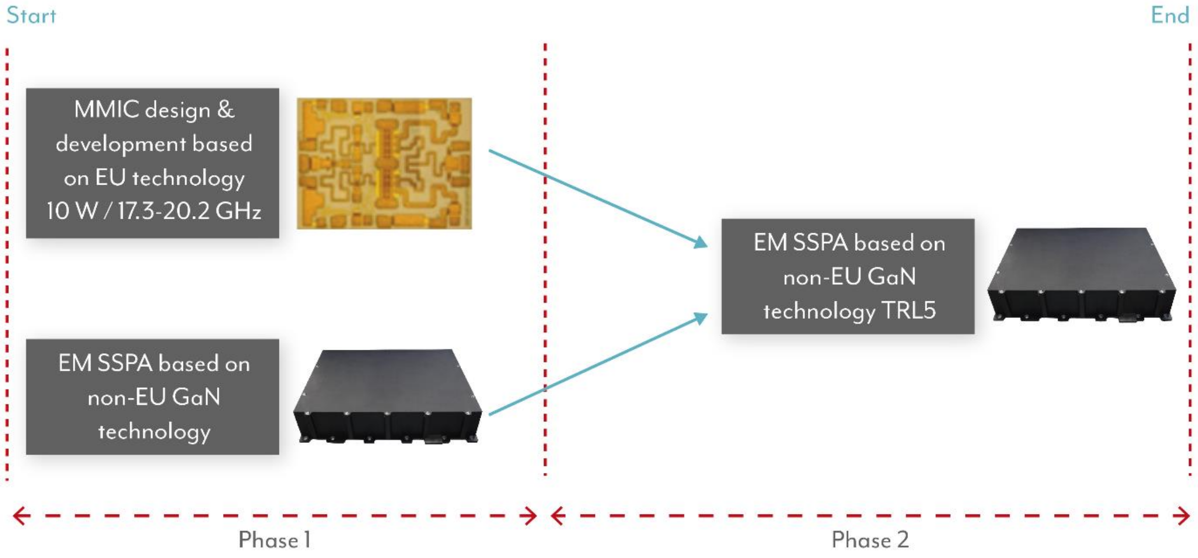

FIGURE 1. FLEXGAN Phases

FLEXGAN Consortium is comprised by five partners from three European countries: TTI leading the project and TECNALIA from Spain, AIRBUS and OMMIC from France and UNITOV from Italy. The Consortium includes industrial partners TTI (SME), OMMIC (SME) and AIRBUS, as well as one academia partner from one university, UNITOV, and from one research organization, TECNALIA.

As can be seen in next diagram, the Consortium is well balanced and covers all the supply chain needed to develop the project with success: from the GaN European manufacturer (OMMIC) and requirements identification of final user (AIRBUS), passing through modules design (UNITOV, TTI and TECNALIA), development and SSPA integration (led by TTI), up to TRL5 verification activities (TECNALIA).

FLEXGAN project was divided into two reporting periods. The first one from M1 until M18, i.e. from 01.11.2018 till 30.04.2020, and the second one from M19 till the end of the project in M36. This document details the work carried out during the first year of FLEXGAN and it is not linked to a reporting period. The periodic report will be done within 60 days following the end of each reporting period.

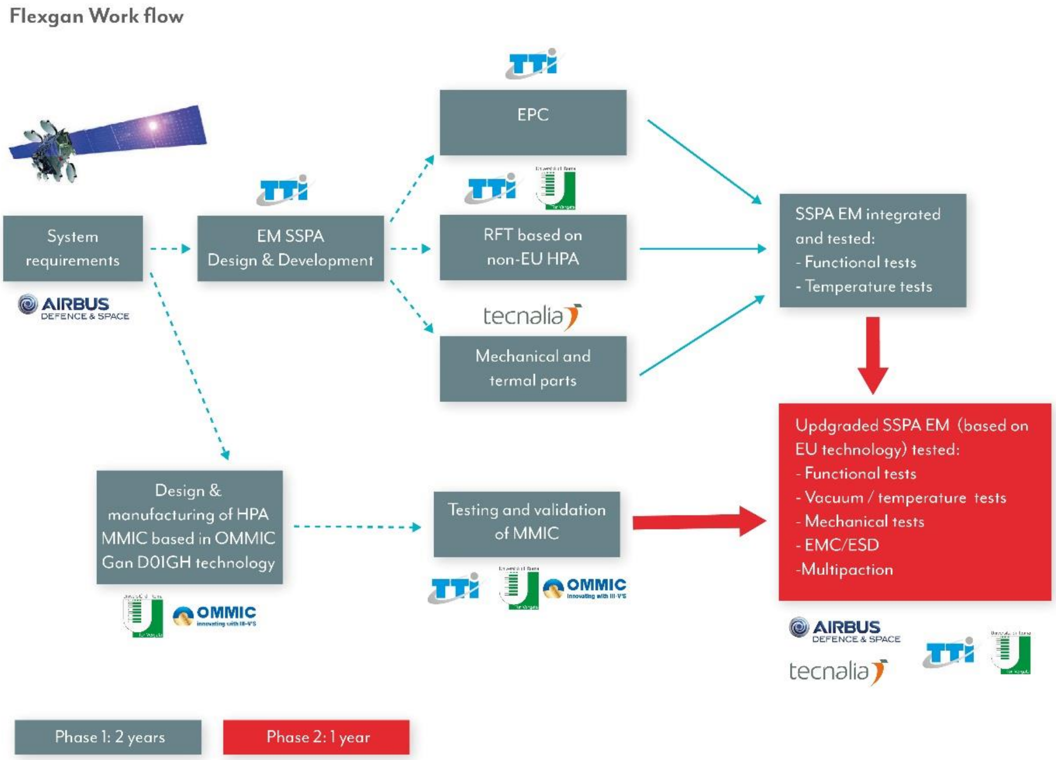

FIGURE 2. FLEXGAN consortium

1.2. Work Performed from the Beginning of the Project to the End of the Period Covered by the Report and Main Results Achieved So Far

As aforementioned, this report covers the work performed from the beginning of the project to the end of the second year of the project, from 01.11.2018 to 31.10.2020. The technical activities developed within this period have been focused on:

- Defining, implementing, maintaining and controlling the overall FLEXGAN Product Assurance Programme.
- Establishing the specific requirements for FLEXGAN SSPA and provision of up to date usage cases for SSPA.
- Defining the baseline architecture.
- The design, manufacturing and testing of HPA GaN MMIC based on D01GH GaN technology from OMMIC (1st iteration): on-wafer and CW test campaign.
- The design, development and test of highly efficient combination techniques.
- The design of the power module based on the non-EU MMIC and on the MMIC based on OMMIC technology.
- Complete detailed design of both SSPAs (based on non-EU MMICs and designed EU MMICs): RF, EPC and mechanical and thermal subsystem.
- Definition, implementation and control of the Innovation Management plan.
- Establishing a preliminary business plan.
- Defining an initial exploitation plan.
- Establishing the FLEXGAN verification programme.

- The retrofit design of HPA GaN MMICs based on D01GH GaN technology (2nd iteration) considering the results of the measurements of the MMICs developed in the first iteration (on-wafer and CW test campaigns).
- Prototyping of SSPA parts: design, implementation and characterization
- Manufacture, assembly and characterization of subsystem units or complete subsystems (for example, control subsystem).
- Carrying out different dissemination and communication activities.

FLEXGAN Product Assurance plan has been defined and established as a mandatory basis for the entire project development. FLEXGAN Product Assurance plan has been defined according to ECSS standards by adapting them to the scope and timeline of the project. FLEXGAN Product Assurance has been implemented and monitored during all phases active during this time, especially in the design phase where dependability analysis (Part Stress, Reliability prediction, worst case analysis, etc) were performed. In addition, product assurance documentation was released after the design (declared 'as designed' lists, design verification matrix, etc.). Quality assurance programme has been followed throughout the project: identification and coding of documents and items, control of waivers and deviations, management and control of non-conformities, reception inspection, supervision and monitoring during manufacturing, assembly and integration, etc.

Relevant and detailed specifications (equipment definition, electrical, mechanical, operability, EMC, pre-launch, launch and in-orbit environment, etc) have been established at different levels, with the aim of guaranteeing the development and production of an SSPA adapted to the space 5G market. These specifications have been established in agreement between all the members of the project (based on initial analysis and previous background).

Baseline SSPA architecture has been defined to meet system requirements and challenges established at system level. The main subsystems and their different stages have been identified, their requirements established and the interfaces between modules detailed. Three main subsystems have been defined and their main functions and characteristics described: Radiofrequency Tray (RFT), Electronic Power Conditioner (EPC) and Mechanical and thermal subsystem (MEC). In order to meet the system demands, each subsystem was also defined, and its characteristics established as a basis to start the detailed designs.

The GaN MMIC design has been carried out during this period to meet the challenging requirements on output power while targeting the efficiency and linearity performance as high as possible. To mitigate risks, three different MMICs have been designed (named as HPA1, HPA2 and HPA 5). Two of them share the same architecture, power budget and active periphery but different passive structure whereas the third is based on a balanced structure with Lange couplers, and different power budget. Shunting balance resistances have been inserted into the internal loops of the three MMICs to prevent possible odd mode oscillation, obtaining almost the same simulation results as before (HPA3, HPA4 and HPA6). Finally, 6 different MMICs designs have been realized. Circuit, Electromagnetic, Monte Carlo, small and large signal stability simulations have been carried out for all proposed MMIC solutions. Considering the simulation results all designs comply with the established specifications. After performing the DRC of the Gds files, reticule was arranged and approved, and finally, the wafer manufacturing began. Two wafer runs have been manufactured and an exhaustive test campaign has been carried out. A good match has been obtained between simulations and on-wafer test results. CW measurements were carried out on special test-jigs, achieving very promising results and allowing to collect sufficient data to confidently redesign a second wafer run. Based on the simulation and test results of the first MMICs, a retrofit design has been completed during the second year of the project to resolve the deviations, optimize parameters and ensure the compliance with requirements in the full frequency band.

Two highly efficient combiners were selected as the most suitable for FLEXGAN, the Radial Combiner (RC) and the Spatial Power Combiner (SPC). Both structures have been fully designed: Electromagnetic, thermal and mechanical designs have been performed. Passive versions of both solutions have been manufactured, assembled and tested. In both cases, a good correspondence between the measurements and the simulations has been achieved. Finally, a thorough assessment of the advantages and disadvantages of both combiners has been carried out for the FLEXGAN SSPA. Finally, RC was selected as a baseline for FLEXGAN.

Power modules based on non-European GaN MMIC and on developed MMIC (D01GH) have been designed as a hybrid modules following ECSS-Q-ST- 60-05C standard (hermeticity, multipactor, thermal dissipation, size, etc.). A complete characterization of them has been carried out.

5G SSPA has been designed in detail. Starting from a general description of the overall SSPA and the block diagram of each subsystem, the detailed designs of all the RFT and EPC subunits have been performed based on either experimental (prototypes) and/or simulation results. Likewise, a mechanical subsystem based on composite electronic enclosure has been designed seeking for mass savings, validating through numerical analysis the thermal and mechanical behaviour in accordance with the established requirements and load cases. FLEXGAN Design Verification Matrix has been issued. Complete manufacturing and assembly information has been produced. The detailed design of the 5 G SSPA has required a collaborative work among all the partners involved in the design of the different subsystems.

A complete verification programme has been defined, mainly focused on establishing the test plan to be followed in the verification activities of FLEXGAN SSPAs. The test plan, test specifications and test procedures to be applied to both EM SSPAs (based on non-European GaN and based on 'ad-hoc' designed FLEXGAN MMICs) were detailed to verify their compliance with the electrical performance requirements. The first verification control document was issued.

Prototypes of different units have been manufactured, assembled and tested. Thanks to them, it has been possible to retune the designs to meet the specifications in advance and have more confidence in the design before starting manufacturing.

All components, pieces or parts of the subsystems have been purchased, manufactured and assembled. Most of the subsystem stages have already been adjusted and characterized. All characterized parts behave as expected according to the design results. It is expected to complete the RFT and EPC characterization and SSPA integration in a short period, to begin with the 5G EM SSPA test campaign.

Furthermore, a significant effort has been devoted to the communication, dissemination and exploitation of FLEXGAN starting from the definition and implementation of its plans. The project aims to provide a strong impact through the wide dissemination of its outcomes and the active communication of its achievements and activities. FLEXGAN communication channels and material been prepared during this time focused on the public disclosure of the project and its objectives. First technological breakthroughs of FLEXGAN project in the field of GaN MMIC power amplifier and combining techniques for SSPAs for next generation 5G satellite have been disclosed in different prestigious international publications.

From a management point of view, the work has been dedicated to coordinating the work among the FLEXGAN consortium in order to ensure the successful completion of the project's objectives according to its schedule.

1.3. Progress Beyond the State of the Art, Expected Results until the End of the Project and Potential Impacts (including the Socio-Economic Impact and the Wider Societal Implications of the Project So Far)

FLEXGAN supposes disruptive innovation because it changes the nature of competition in the marketplace and lead to the creation of new ventures. Its innovation relies on the development of novel, fast and cost-effective high power SSPAs based on GaN technology, which are able to provide the same services as TWTAs but with other benefits such as graceful degradation, lower supply voltages, lower cost and better integration (after adapting it) in case of phased-array and multi-spot systems.

The objective is to design, develop and test in a representative space environment (TRL5) a low cost, highly efficient and flexible SSPA in the Ka band aimed at developing a future Flight model to be used in satellite payloads. It is based on D01GH OMMIC European GaN technology and implements a highly innovative and low loss recombination scheme.

FLEXGAN SSPAs represent a new advance in the application of GaN solutions to spacecraft payloads, helping to eliminate the gap in the application of GaN technology to space models. FLEXGAN adopts an aggressive strategy based on launching a novel amplifying solution that seeks to achieve a leading position in the satellite market.

FLEXGAN SSPAs are specifically geared towards a Flight model to be used on board the next generation vHTS satellites to be deployed in the 5G ecosystem. Satellite systems are key components to provide 5G services, augmenting their capability and addressing some of the major challenges: increasing connectivity and reducing cost per bit. FLEXGAN SSPAs will promote the integration of satellites communications in 5G, enabling reliable and flexible amplification of the 5G signal within satellites, 'key' to allow access to broadband internet access anywhere/anytime. Also, they will lead to reduce the CAPEX and OPEX in the 5G radio networks.

Also, FLEXGAN will contribute to increase the competitiveness of the different stakeholders in the European Space industry and create new business opportunities around the space market. Thanks to the achievements of FLEXGAN, different products based on GaN will be developed for the space market, either for the space or ground segment. FLEXGAN technologies could be also applied to ground products in commercial and military markets. The technology will allow spin-off products (LNAs, switches, sensors,…) for being installed in hub stations and user terminals. The competitiveness of project partners will be strengthened thanks to apply the novel technologies investigated and developed within FLEXGAN to other fields

Moreover, new job opportunities will be created within the project, promoting the growth of qualified technical employment. FLEXGAN will stimulate the integration of space into European society and bring benefits to European citizens. In addition, it contributes to European research and technology ecosystem.

Focusing on technology breakthroughs made during the first two years of the project, the outstanding characteristics of the realized GaN MMICs, validated during the carried-out exhaustive test campaign, will place them in the state-of the art of the technology. The developed MMICs offer a cost-effective European solution comparable in terms of frequency bandwidth, output power and efficiency to the latest reported state of the art SiC GaN MMICs. On the other hand, the promising results obtained in the different parts of the subsystem already developed, such as GaN based DC/DC converters or CFRP housing, allow to anticipate that the final amplifier will have an unbeatable performance in weight and efficiency for an SSPA capable of amplifying without distorting a multi-carrier signal up to a power of 125 W.