Deliverable D12:
Executive Summary Report

"Single-chip Ka-band Doherty amplifier"

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Second Version	2	0	02/08/2023
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Reason for change	**Architecture**	**section**	**Page**
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1. SUMMARY

The GAN Doherty AmpLiFier (GANDALF) project aimed to develop and evaluate Gallium Nitride (GaN) based Doherty Power Amplifiers (DPAs) for advanced satellite communication systems (17.3-20.3 GHz).

The project foresaw a 24-months duration but, due to many concurrent reasons, it extended to three years more. The technical activities were completed in March 2023. The main reason for the significant delay has been the SARS COVID-19 pandemic. Another reason that aggravated the situation was the difficulty related to the assembly and testing of the chips, which required several successive shipments of material among the partners and several re-adjustments of the assembly and test plan. These adjustments were particularly time consuming after Brexit, whenever CU was involved in the exchanges, and when the assembly lines at TAS-I were not available due to other simultaneous activities. In fact, to attempt at speeding up the assembly process, another company (Iconic RF, in Belfast) was involved for the 2nd run assemblies.

The 24-month project was originally divided into two logical and successive temporal phases:

PHASE 1: Originally planned to have a duration of 6 months.

PHASE 2: Originally planned to have a duration of 18 months.

The goal of PHASE 1 was to conduct a comprehensive literature review and evaluate available European GaN processes. This phase aimed to select a suitable technology and process and propose Doherty MMIC PA design solutions that could fully meet the performance requirements.

In PHASE 2 the focus has been on the manufacturing and characterization of the DPA MMICs, as well as the possible (not completed) integration of selected samples into connectorized modules. Two foundry runs were carried out during the 18-month duration of this phase (largely expanded for the COVID-19 pandemic related issues).

The task division has been the following:

- Coordination of the project and Design of the MMICs: MECSA
- CW characterization, including thermal and load pull measurements: Cardiff University
- System level characterizations: IT Aveiro
- Fabrication of the MMICs: MACOM (formerly OMMIC during the project)
- Integration: Thales Alenia Space ITALY

Apart from the large time delay, the project successfully achieved most of its objectives, surpassing the state-of-the-art in terms of linearity and Noise to Power Ratio (NPR) performance and demonstrating the feasibility of Doherty multi-stage MMIC operating in K band with significant output power and very good linearity.

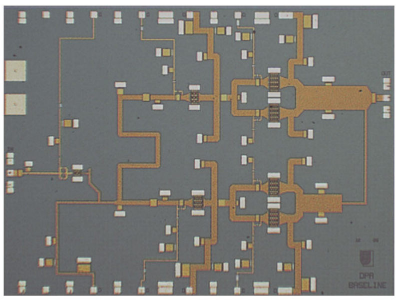
Some numbers to summarise the huge effort the consortium put in the development of the project activities:

- **4** DPA architectures designed in the 1st foundry run
- **2** DPA architectures (in two variants) designed in the 2nd foundry run
- **3** additional HPA architectures designed in the 2nd foundry run for comparison with the DPAs
- **5** wafers produced by OMMIC (2 in the 1st foundry run, 3 in the 2nd foundry run)
- **20** connectorized modules built

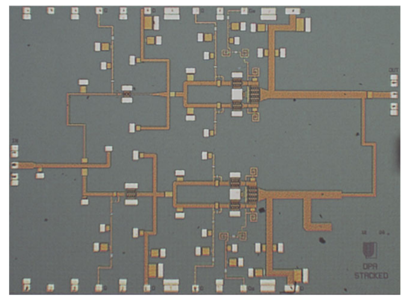
Figure 1 summarizes the designed and fabricated architectures. The best performing ones in the 1st foundry run resulted to be the Multi-Doherty (Lizard, Maze) and the Stacked. At the end of the project, the MDPA Balanced produced in the 2nd foundry run, which is the re-designed evolution of the multi-Doherty strategy, resulted the best performing. However, the Stacked one, especially in the self-bias configuration demonstrated very promising results and is identified as a very good candidate for future developments, once the stability issue typical of the architecture is completely solved.

Throughout the project, the consortium's expertise and collaboration with the Agency enabled ground-breaking advancements in DPA design techniques. The results demonstrated outstanding linearity performance, surpassing previous benchmarks. Notably, the project achieved record-breaking results in terms of NPR, showcasing the potential of GaN-based DPAs in delivering improved signal quality and mitigating nonlinear distortions.

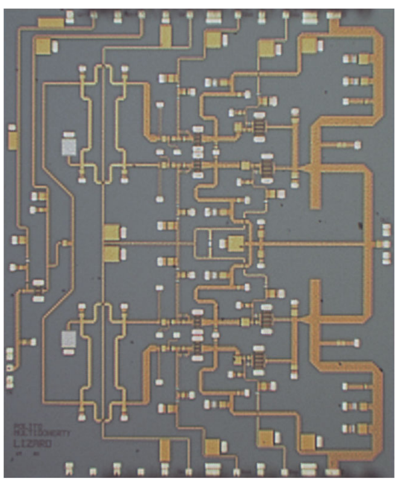
First Run



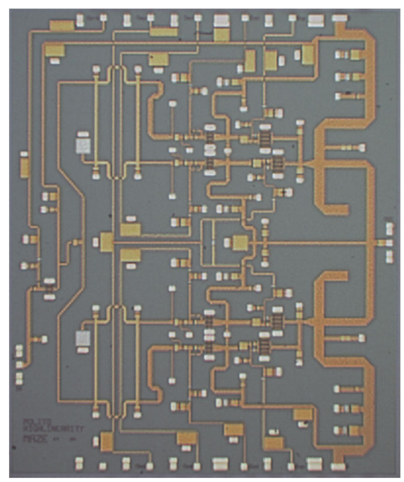
Baseline



Stacked

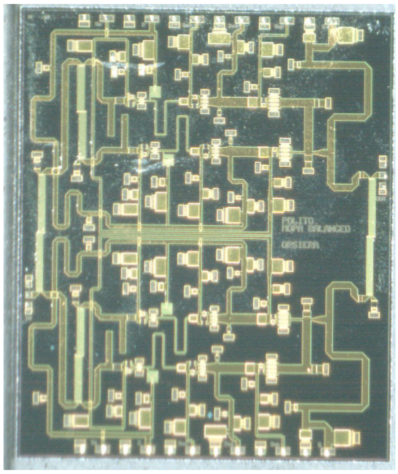


Multi-Doherty (Lizard)

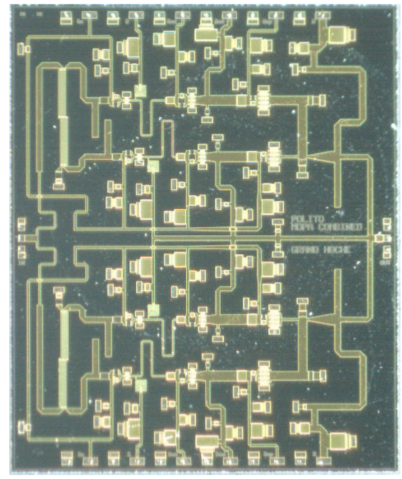


High-linearity (Maze)

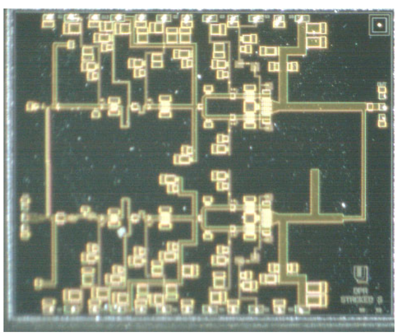
Second run



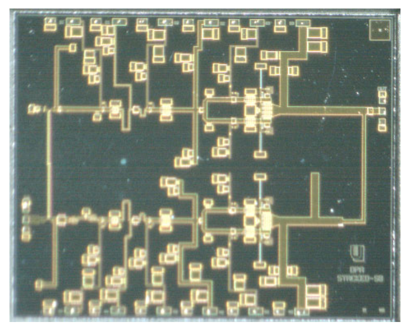
MDPA Balanced



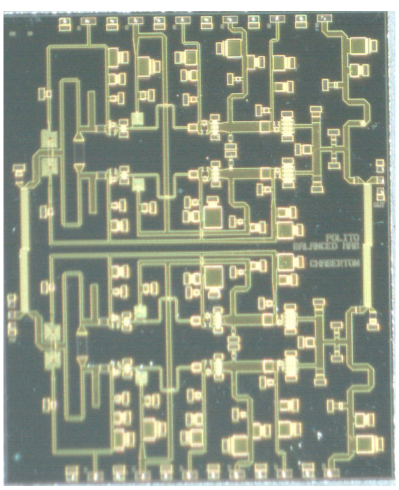
MDPA Combined



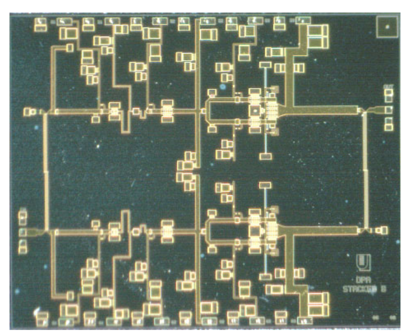
Stacked-S



Stacked-SB



Balanced MAB



Stacked-B

Figure 1 Microscope pictures of the MMIC architectures fabricated during the project.

2. Challenges and Conclusions

One of the main challenges of the project was to determine if the Doherty architecture, well known for its higher backoff efficiency compared to conventional corporate PAs, would still be competitive in a real-case scenario. We needed to address concerns regarding the higher complexity of the architecture, the possible reduction in robustness, the increased number of required biases, and, importantly, the linearity aspects that could potentially diminish the theoretical advantages.

Based on our experimental results, we strongly believe that, when properly designed to achieve the required levels of linearity and robustness, the Doherty architecture proves to be a winning solution.

In Figure 2, we compare the power sweeps of the Balanced MAB and the corresponding MDPA Balanced in CW large signal conditions, from 17.3 GHz to 20.3 GHz. The Balanced MAB exhibits a slightly higher small signal gain (approximately 3 dB). However, the saturated power and efficiency are very similar for the two amplifiers. At 6 dB OBO, as expected, the MDPA's efficiency is significantly higher (more than 10 points) compared to the Balanced MAB. Remarkably, the very good Doherty efficiency performance is accompanied by an excellent linearity, which is comparable if not slightly better than that of the class-AB version.

This ultimately allows to conclude that a DPA that provides advantages in terms of efficiency compared to the standard class-AB solution while maintaining a comparable linearity can be designed, with limited added complexity at chip level. Finally, the proposed DPA also features isolated splitters and combiners at the input and output, thus also providing robustness against load variations. Therefore, the outcomes of the project suggest that the DPA is indeed a valid alternative to standard class-AB PAs for applications adopting variable-envelope signals with PAPR around 6 dB. This may the case for multi-carrier and variable envelope applications, where adopting a Doherty architectural solution can yield significant benefits.

The implementation of DPA architectures presents a cost increase compared to corporate class AB solutions. This arises from the heightened architectural complexity, necessitating more biases and introducing asymmetry in active devices chains. Consequently, the resulting designs tend to be less robust. Additional challenges entail the requirement for dependable models of class C devices and maintaining gain flatness, especially in scenarios with wide bandwidths. These potential limitations could impact the success of DPAs in the satellite communications domain. Nonetheless, if modulation strategies evolve toward multi-carrier and variable envelope solutions, the efficiency enhancements offered by DPAs may render them more appealing.

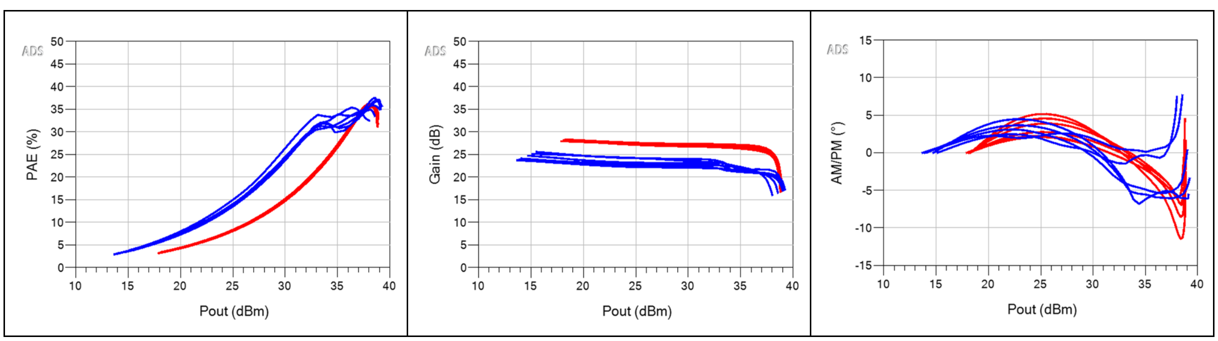


Figure 2: Large signal power sweeps comparison of Balanced MAB (red) and MDPA Balanced (blue) from 17.3 GHz to 20.3 GHz, with 0.5 GHz steps, at 25°C.

A limitation of the conclusions drawn by this project may reside in the instantaneous bandwidth of the adopted signals. In this project, the gain flatness and the linearity requirements had to be satisfied under 100-MHz signal excitation. The extensive NPR measurement campaign shows that with such signals the linearity of the MDPA Balanced is excellent, while it degrades if the instantaneous bandwidth of the signal is of the order of few GHz. This is related to the difficulty of controlling and minimizing the nonlinear memory effects of the transistors over such bandwidths, as well as to the gain flatness over the whole RF bandwidth. These aspects were not directly explored in this project, but it is fair to assume that ensuring appropriate gain flatness and linearity over GHz bandwidths will be more challenging in a DPA design than in a class-AB PA design. However, conclusive proof regarding this aspect can only be gained by further activities specifically dedicated to exploring wider bandwidths.

The issues encountered during the project were related to a combination of factors including the technology maturity, the complexity of the designs and the deliberate choice to pursue advanced and challenging design choices, as necessitated by the nature of an exploration activity, in order to achieve greater added value. This decision to push the boundaries with unconventional design approaches introduced additional complexities and risks. While these choices offered the potential for significant advancements, they also contributed to the challenges faced in realizing optimal results across all project objectives. Despite these challenges, the project team proactively managed deviations and communicated them transparently to the Agency, ensuring effective coordination and problem-solving.

The GANDALF project achieved significant breakthroughs at the design level, particularly in the development of multi-stage Doherty architectures using elementary DPA cells. The innovative design approach allowed for enhanced power combining and improved efficiency, and unpreceded linearity. Additionally, the utilization of a stacked architecture for power combination showed great potential in achieving higher levels of output power.

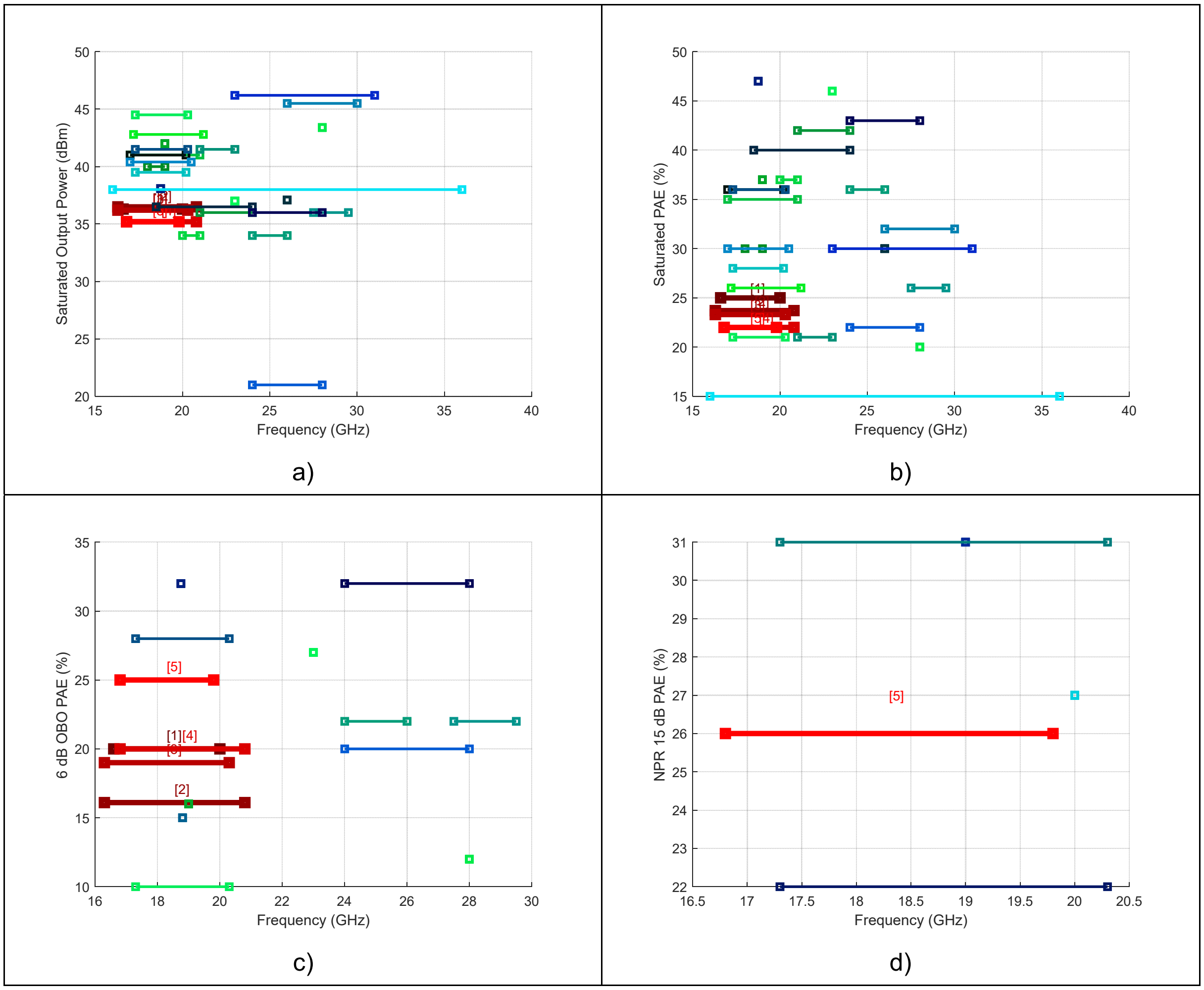
The preliminary results obtained from these design innovations were highly encouraging, promising significant performance enhancements in terms of output power, gain, efficiency and linearity.

However, it is important to note that the full exploitation of the stacked approach was hindered by many factors, from the complex and challenging design strategy prone to possible instabilities to the not complete maturity of the manufacturing process. While the preliminary results demonstrated the attractiveness of this design concept, the limited repeatability of the manufacturing process prevented its optimal implementation. Nevertheless, the success of the initial design investigations suggests that further development and refinement of the stacked architecture could lead to even more remarkable outcomes in future iterations.

The achievements at the design level highlight the project's potential for future developments and follow-up initiatives. The innovative multi-stage Doherty architectures and the exploration of stacked power combining present exciting opportunities for further enhancements in power amplification and efficiency. By addressing the challenges posed by the process immaturity and capitalizing on the knowledge gained from the GANDALF project, future activities could leverage the stacked architecture to achieve unprecedented levels of performance. These design advancements, combined with ongoing research and development efforts, will continue to propel the field of GaN-based DPAs and unlock their full potential for advanced satellite communication systems and beyond.

Furthermore, the project benefited significantly from the state-of-the-art measurement system employed, especially regarding the NPR characterization to evaluate the linearity performance. With its capability to measure NPR with instantaneous bandwidths exceeding 2 GHz, the measurement system of IT provided accurate and comprehensive insights into the DPA's performance, enabling thorough evaluation and validation of the achieved results and opening up new research topics.

The MDPA balanced amplifier has been compared with the present state of the art in terms of saturated output power, PAE (both at saturation and at 6 dB OBO) and linearity (NPR). In the latter case we adopted the most stringent configuration for the MDPA, adopting Gaussian distribution and 10 dB PAPR.


Saturated Output Power (dBm)
Frequency (GHz)
a)
Saturated PAE (%)
Frequency (GHz)
b)
6 dB OBO PAE (%)
[5]
[1][4]
[2]
Frequency (GHz)
c)
NPR 15 dB PAE (%)
[5]
Frequency (GHz)
d)

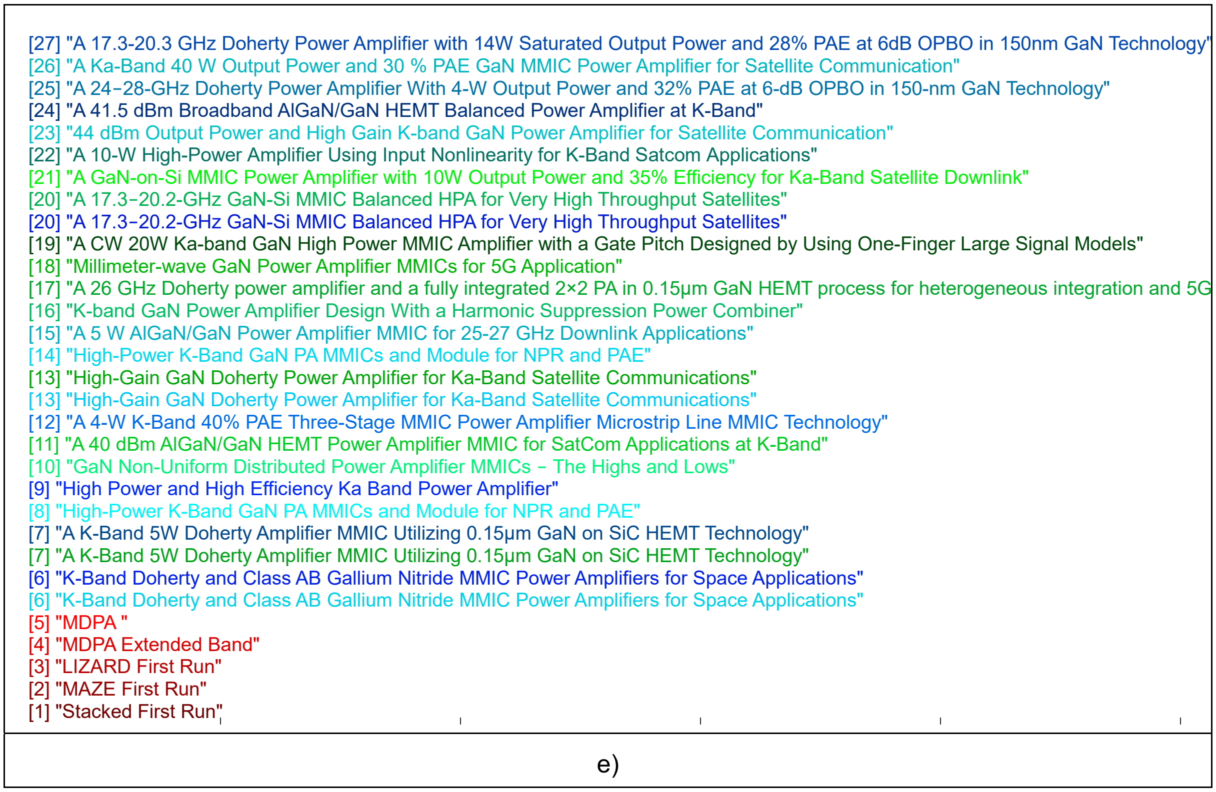


Figure 3 Comparison of the MDPA architecture (red solid line) with the present state of the art in terms of saturated output power (a), saturated PAE (b), 6 dB OBO efficiency (c) and PAE @ 15 dB NPR for Gaussian signal 10 dB PAPR and 100 MHz instantaneous bandwidth (d). The references are shown in (e).

As shown in Figure 3 the hardware presented in this study demonstrates good performance in terms of output power and saturated efficiency, with slightly lower values compared to GaN-SiC substrate technologies. However, the 6 dB output back-off (OBO) efficiency stands out as one of the highest reported in the literature. The few NPR measurements available in the literature also position the MDPA in a favourable position.

It is important to note that the linearity of the MDPA is highly competitive based on the selected stimulus (uniform or Gaussian) and instantaneous bandwidth (ranging from 100 MHz to 2.9 GHz). In all cases, the MDPA remains among the most linear examples currently available in the literature. These results demonstrate the effectiveness of the MDPA design and its capability to provide excellent efficiency and linearity, making it a strong contender for high-performance power amplification in communication systems.

3. NOVELTY

The project has brought about numerous innovations, introducing novel concepts and techniques in the field of power amplifiers. Some of the key innovations include:

- Stacked Topologies in DPA: The adoption of stacked topologies in a DPA architecture represents a novel approach to enhance efficiency and gain. By combining multiple power amplifiers in a cascaded manner, the DPA can achieve improved performance and handle higher power levels while maintaining linearity.

- Self-Biasing Technique: The use of self-biasing in multistage stacked architectures simplifies the biasing network and routing, making the overall design more efficient and compact. This innovation helps reduce the complexity of the circuit and enhances its robustness.

- Modularity in DPAs (Combination of DPA Unit Cells): The project highlights the significance of modularity in DPAs. The approach of designing a DPA unit cells based on individual transistors allows for more flexible and scalable designs, where individual unit cells can be easily combined to achieve the desired power levels and performance characteristics.

- Impact of Combiners: The research investigates the impact of different types of combiners, including isolated and non-isolated combiners, on DPA performance. Understanding their influence on efficiency, linearity, and other parameters is a crucial step towards optimizing DPA designs for specific applications.

- Effect of Drivers' Position and Size on Linearity: The project explores the effect of the driver's position and size within the DPA architecture. This investigation sheds light on how the positioning and size of the driver stage can impact overall linearity and efficiency, leading to valuable insights for further design improvements.

Overall, these innovations contribute to advancing the state-of-the-art in power amplifier technology, paving the way for more efficient, compact, and high-performance solutions that can cater to the demanding requirements of modern communication systems.

4. IMPACT

The project produced **11 publications,** 3 on international journals and 8 presented at the major conferences of the sector:

1. A. Piacibello *et al.*, "A 5-W GaN Doherty Amplifier for Ka-Band Satellite Downlink With 4-GHz Bandwidth and 17-dB NPR," in ***IEEE Microwave and Wireless Components Letters***, vol. 32, no. 8, pp. 964-967, Aug. 2022, doi: 10.1109/LMWC.2022.3160227.
2. A. Piacibello, P. Colantonio, R. Giofrè and V. Camarchia, "Doherty Power Amplifiers for Ka-Band Satellite Downlink," *2022 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR)*, Las Vegas, NV, USA, 2022, pp. 18-21, doi: 10.1109/PAWR53092.2022.9719849.
3. F. Costanzo *et al.*, "A GaN MMIC Stacked Doherty Power Amplifier For Space Applications," *2022 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR)*, Las Vegas, NV, USA, 2022, pp. 29-31, doi: 10.1109/PAWR53092.2022.9719789.
4. R. Figueiredo, N. B. Carvalho, A. Piacibello and V. Camarchia, "Nonlinear Dynamic RF System Characterization: Envelope Intermodulation Distortion Profiles—A Noise Power Ratio-Based Approach," in ***IEEE Transactions on Microwave Theory and Techniques***, vol. 69, no. 9, pp. 4256-4271, Sept. 2021, doi: 10.1109/TMTT.2021.3092398.
5. F. Costanzo, A. Piacibello, M. Pirola, P. Colantonio, V. Camarchia and R. Giofrè, "A Novel Stacked Cell Layout for High-Frequency Power Applications," in ***IEEE Microwave and Wireless Components Letters***, vol. 31, no. 6, pp. 597-599, June 2021, doi: 10.1109/LMWC.2021.3073219.
6. A. Piacibello, R. Giofré, R. Quaglia and V. Camarchia, "34 dBm GaN Doherty Power Amplifier for Ka-band satellite downlink," *2020 15th European Microwave Integrated Circuits Conference (EuMIC)*, Utrecht, Netherlands, 2021, pp. 25-28.
7. R. Figueiredo, A. Piacibello, V. Camarchia and N. B. Carvalho, "Swept Notch NPR for Linearity Assessment of Systems Presenting Long-Term Memory Effects," *2020 95th ARFTG Microwave Measurement Conference (ARFTG)*, Los Angeles, CA, USA, 2020, pp. 1-4, doi: 10.1109/ARFTG47271.2020.9241380.
8. A. Piacibello, F. Costanzo, R. Giofrè, D. Hayes, R. Quaglia and V. Camarchia, "GaN Doherty MMIC Power Amplifiers for Satellite Ka-band Downlink," *2020 International Workshop on Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMiC)*, Cardiff, UK, 2020, pp. 1-3, doi: 10.1109/INMMiC46721.2020.9160047.
9. R. Quaglia *et al.*, "Source/Load-Pull Characterisation of GaN on Si HEMTs with Data Analysis Targeting Doherty Design," *2020 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR)*, San Antonio, TX, USA, 2020, pp. 5-8, doi: 10.1109/PAWR46754.2020.9035999.
10. A. Piacibello, R. Figueiredo, V. Camarchia, M. Pirola and N. B. Carvalho, "Linearity-aware design of Doherty power amplifiers," *2019 IEEE MTT-S International Microwave Conference on Hardware and Systems for 5G and Beyond (IMC-5G)*, Atlanta, GA, USA, 2019, pp. 1-3, doi: 10.1109/IMC-5G47857.2019.9160390.
11. V. Camarchia, A. Piacibello and R. Quaglia, "Integrated Doherty power amplifiers for satellite systems: challenges and solutions," *2019 IEEE Topical Workshop on Internet of Space (TWIOS)*, Orlando, FL, USA, 2019, pp. 1-4, doi: 10.1109/TWIOS.2019.8724532.

The outcomes of the GANDALF project hold good promise for the advancement of satellite communication systems. The very good linearity and NPR achievements pave the way for enhanced signal quality, reduced distortions, and improved overall system performance. The success of the project underscores the importance of continued research and development in GaN-based RF amplifier technology, with potential applications in diverse industries and sectors.

Moving forward, the project has provided valuable insights and identified areas for further improvement. The project team has presented proposals to the Agency, outlining future steps to advance the DPA technology toward higher Technology Readiness Levels (TRLs), addressing the challenges encountered during the project and capitalizing on the promising performance achieved.

In conclusion, the GANDALF project has pushed the boundaries of DPA technology, achieving remarkable results in terms of linearity and NPR performance. The collaboration between the consortium, the Agency, and the utilization of cutting-edge measurement systems has propelled the project's success and established a solid foundation for future advancements in GaN-based DPAs.