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Transatlantic testbed for LEO Satellite mega-constellations
Deliverable 3: Experiment Results and Final Report

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Deliverable 3: Part I

Analysis, results, and wider impact

1 Abstract

We built and designed two sets of experiments: (1) Inter-domain routing experiments, and (2) measuring resilience to disruption and failure. The focus of the first experiment is to understand how existing routing protocols, specifically, Open Shortest Path First (OSPF) performs when deployed in highly dynamic networks such as LEO networks. On the other hand, the main purpose of the second experiment is to emulate disruptive events (e.g., satellite failures) and measure how that would impact the performance of the whole mega-constellation in terms of latency, packet losses, path stretch and re-routing. For the routing experiments, we observed that while single-area configuration for OSPF routing protocol never converge for Starlink mega-constellation, the multi-areas OSFP configuration converge in **55 seconds** which is considered to be slow convergence time and cannot cope with the high dynamics of LEO networks. For the resilience experiment, we observed **1.6x times** increases in the Ping RTT when a single satellite fails in the path between Tokyo and Los Angeles.

2 Project Vision

The vision of this project is the same as provided in D2. We aimed to inter-connect the two testbeds across the Atlantic to demonstrate experiments that will allow us to contribute to building a more resilient Internet from space. Such a resilient network is crucial because Internet connectivity from space can be deployed quickly at scale during critical events as recently demonstrated during the Ukraine War. Such connectivity can also help during natural disasters, etc., and such critical connectivity will need to be more resilient to failure. This project will also enable us to propose techniques that would enable more efficient Internet from space with interoperability between different competing mega-constellations, through sharing connectivity and potentially sharing data for efficient interconnectivity.

3 Details on participants (both EU and US)

Prof. Nishanth Sastry is Research Director of Department of computer science, Co-Lead of the Distributed and Networked Systems Group in the Department of Computer Science, University of Surrey, Co-Director of pan university Surrey Security Network. He is also a Visiting Researcher at the Alan Turing Institute, where he is a co-lead of the Social Data Science Special Interest Group. Prof. Sastry holds a Bachelor's degree (with distinction) from R.V. College of Engineering, Bangalore University, a Master's degree from University of Texas, Austin, and a PhD from the University of Cambridge, all in Computer Science. Previously, he spent over six years in the industry (Cisco, IBM TJ Watson Research Center). He will provide networked systems expertise and has previous experience helping setup nationally important testbeds, including King's College London's node of the first end-to-end 5G testbed in the UK.
Prof. Sastry: Higher Education Innovation Fund Strategic Grant: Testbed to enable Research into Distributed and Networked Systems in Space Total award: £196,504, Duration: April 2021 – Jul 2022.

- Synopsis: OneWeb, Starlink and others have recently proposed creating constellations of small satellites, in the hundreds or thousands – a scale never seen before. The vision of achieving networked connectivity among so many distributed entities in space creates novel research challenges in Distributed and Networked Systems, real-time implementation as well as Cybersecurity. Following significant new recruitments that enabled critical mass, the Department of Computer Science recently created a Distributed and Networked Systems (DANS) group within the Surrey Centre for Cybersecurity. DANS intends to make satellite constellations one of its strategic focus areas, by working with the Surrey Space Centre and Space@VT. This project will create a testbed for experimentation with network and security protocols on satellite constellations. To our knowledge, no other Distributed/Networked Systems group has such a testbed, so this will put Surrey at the forefront of U.K. (and world) research in this area and be a vehicle for future funding and international collaboration.

Prof. Jonathan Black is a Professor in the Department of Aerospace and Ocean Engineering at Virginia Tech, Co-Director of Space@VT, the Director of the Aerospace and Ocean Systems Division (AOSD) within the VT National Security Institute, and the Northrop Grumman Senior Faculty Fellow in C4ISR. He served as PI or Co-PI on five spaceflight experiments. Dr. Black works across academic departments and multiple research centers at the intersection of mission platforms and mission payloads.
Specifically related to this project, Dr. Black is the Co-Director of the Virginia SmallSat Data Consortium (VSDC). The data cube, real-time cloud computing, rural broadband, and AI/ML work of VSDC will be key resources leveraged

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Prof. Black: Commonwealth Cyber Initiative Southwest Virginia Node Grant # 467336 SmallSat Testbed for Cybersecurity and Resiliency; Total award $200,000. Duration: July 2021 – 31 Dec 2022.

- Synopsis: The initial goal of this testbed is to serve as a foundation with which to research satellite-based internet constellations. It is part of an overall project to emulate satellite constellations through scalable hardware and software models. Our collaborators including Space@VT, Wireless@VT, GMU, and the University of Surrey Distributed and Networked Systems Group and Surrey Centre for Cyber Security in the Department of Computer Science in the UK. We plan on linking these testbeds across the Atlantic providing students a unique international experiential educational collaboration. Applications of the scalable satellite testbed include rural broadband, 5G in space, and space cybersecurity. Additional collaborations with external companies and universities are planned following a planned workshop in June-July 2022

Dr. Samantha Parry Kenyon graduated with a PhD in aerospace engineering from the University of Florida's Precision Space Systems Laboratory and worked primarily on the joint ESA-NASA mission LISA (Laser Interferometer Space Antenna) designing, building, and testing electronics for flight, developing the technology from conception to TRL 6. She is currently a Research Associate at Virginia Tech and is involved with numerous research programs through the Center for Space Science and Engineering (Space@VT) and the Virginia Tech National Security Institute (VT-NSI). She has experience with developing space-qualified hardware, building technology to achieve mission requirements. She also has experience working on a small satellite communication mission and an extensive orbital mechanics background.

Dr. James McClure (JM) has 10 years of experience supporting research computing services as well as research expertise in parallel and distributed computing, including both hardware and software components. Previous projects have considered the development of edge computing technologies for mobile UAV teams, which incorporate heterogeneous networks and embedded devices using Kubernetes. These areas significantly overlap with the expected trajectory for future space communications.

Mohamed Kassem received the Ph.D. degree in computer science from The University of Edinburgh, UK, in 2020. He is currently a research fellow at the University of Surrey, UK. Prior to this, he was a Lecturer (Assistant Professor) at the Faculty of Computers and Artificial Intelligent, Cairo University, Egypt. His research interests focus on aspects relevant to the next-generation Internet, wireless, and mobile (5G and beyond) networks, including, LEO satellites mega-constellation, 5G mobile network architecture, vRAN, multi-RAT systems, spectrum sharing, and Universal Internet Access.

Abdullahi Kutiriko Abubakar is pursuing a PhD in Computer Science at the University of Surrey under the supervision of Prof. Nishanth Sastry. Before this, he was a research student at King's College London under Prof. Sastry's guidance. Earlier in his career, he served as an Assistant Lecturer at the Niger State College of Education in Minna. His research interests span IoT, Community Networks, Edge Computing, as well as next-generation communication systems such as mobile networks beyond 5G and the LEO Satellite mega constellations. Abdul's role in the project was to investigate the impact of gateway placement in the emulation platform.

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Vibhor Agarwal is currently a PhD student in the Department of Computer Science, University of Surrey, UK. Prior to this, he completed his Bachelor's in Computer Science from LNMIIT, Jaipur, India and worked in the industry for 1.5 years as a Software Engineer. His main research interests are in programming and developing deep learning frameworks, especially based on graphs. Vibhor assisted Prof. Sastry in planning out project activities and with the logistics of the testbed coordination with the US partners.

4 Results

Testbed Set-up:

We run the following two experiments on the same setup where we have the Mininet-based simulator hosted in a virtual machine running Ubuntu 18.04 (kernel 5.4.0-137) with 26 cores and 115 GB of RAM.

4.1. Experiment 1 – OSPF Routing Performance – Setup:

In this experiment, we run Open Shortest Path First (OSPF) routing algorithm on Starlink Shell-1 mega-constellation which consist of 1485 satellites. We use the Linux-based open-source library ***"Quagga"*** to run the OSPF routing algorithm. We aimed answer two main questions: (1) How fast routing tables in the Starlink Shell-1 mega-constellation needs to be updated. (2) Can OSPF routing algorithm achieve the required fast convergence?

To answer the first question, we need to understand how fast the network topology changes over time for the above mega-constellation. Fig.1 shows the number of topology changes for Ground-Satellite Links (GSLs) and Inter-Satellite Links (ISLs) for an 80 minutes simulation. We observed high dynamic network behaviour with a median of 84 GSLs changes every 50 seconds. We also observed that in 30% of the time there at least 2 changes of ISLs links every 50 seconds across the whole mega-constellation.

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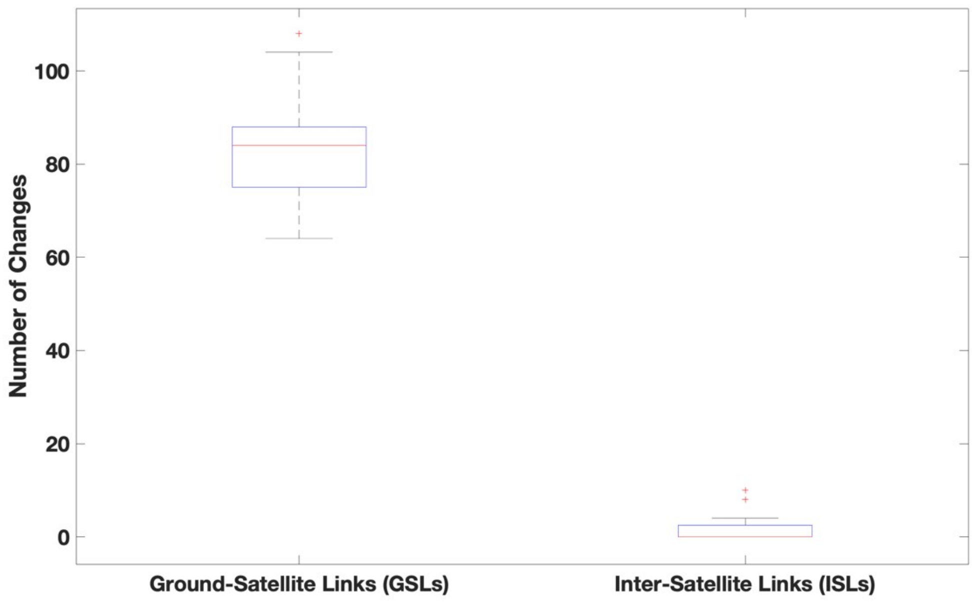

Figure.1: Topology changes in terms of number of GSLs and ISLs

To assess the performance of OSPF routing algorithm, we took two approaches:

1. **Single Area Configuration:** Run OSPF routing algorithm with single area where all the satellites are considered in the same area (i.e., Area 0, See Fig.2a for sample of configurations)
2. **Multi-Area Configuration**: Run OSPF routing algorithm with multiple areas where we configured routers in the same orbits to be with the same area, and all boundary routers on the edge of different orbits to be in the backbone area (i.e., area 0, See Fig.2b for sample of configurations).

```
hostname sat553
password en

router ospf
  ospf router-id 120.0.161.65
  redistribute connected
  network 120.0.161.65/32 area 0
  network 12.0.161.65/28 area 0
  network 12.0.160.226/28 area 0
  network 12.0.161.2/28 area 0
  network 12.0.161.113/28 area 0
  network 12.0.163.81/28 area 0
  network 12.0.163.145/28 area 0

log file /tmp/sat553-ospfdd.log

!
log stdout
```

```
hostname sat553
password en

router ospf
  ospf router-id 120.0.161.65
  redistribute connected
  network 120.0.161.65/32 area 27
  network 12.0.161.65/28 area 27
  network 12.0.160.226/28 area 26
  network 12.0.161.2/28 area 27
  network 12.0.161.113/28 area 0
  network 12.0.163.81/28 area 28
  network 12.0.163.145/28 area 28

log file /tmp/sat553-ospfdd.log

!
log stdout
```

Figure.2: OSPF configuration file for (a) single-area configurations, (b) multi-area configuration

4.1.1. Experiment 1 – OSPF Routing Performance – Results and Analysis:

For the single-area configuration, we observed that the OSPF algorithm never converge when deployed across all satellites in Starlink Shell-1 mega-constellation. The OSPF algorithm (single-area configuration) also fully utilize all the 26 cores of the virtual machine.

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For the multi-area configuration, we have total of 72 areas (1 backbone area, and 71 standards areas) where there are around 20-22 satellites (routers) per area. We observed that in multi-areas setup, OSPF routing algorithm converge after 55 seconds while utilising 60% of the available CPUs. Given the results shown in Fig.1, OSPF considered to be significantly slow and cannot cope with the high dynamic nature of the LEO network. That emphasizes the need to design and implemented a pro-active routing protocol that can predict the changes in the network topology, and pre-compute the routing tables before these changes occurs.

4.2. Experiment 2 – Measuring mega-constellation resilience – Setup:

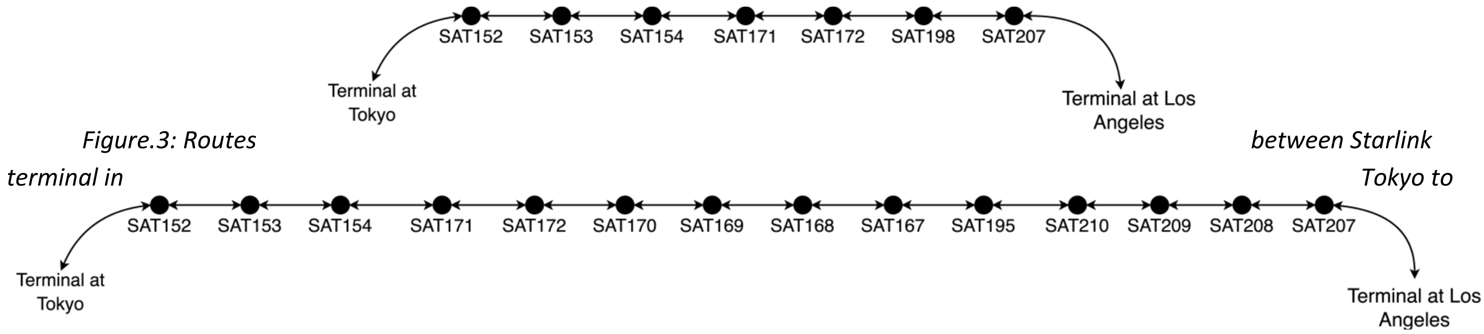

Figure.3: Routes between Starlink terminal in Tokyo to Starlink terminal in LA. In the above sub-figure, there is no satellites failure or disruption events. Second sub-figure: due to the failure of SAT198, the traffic is re-routed through longer path.

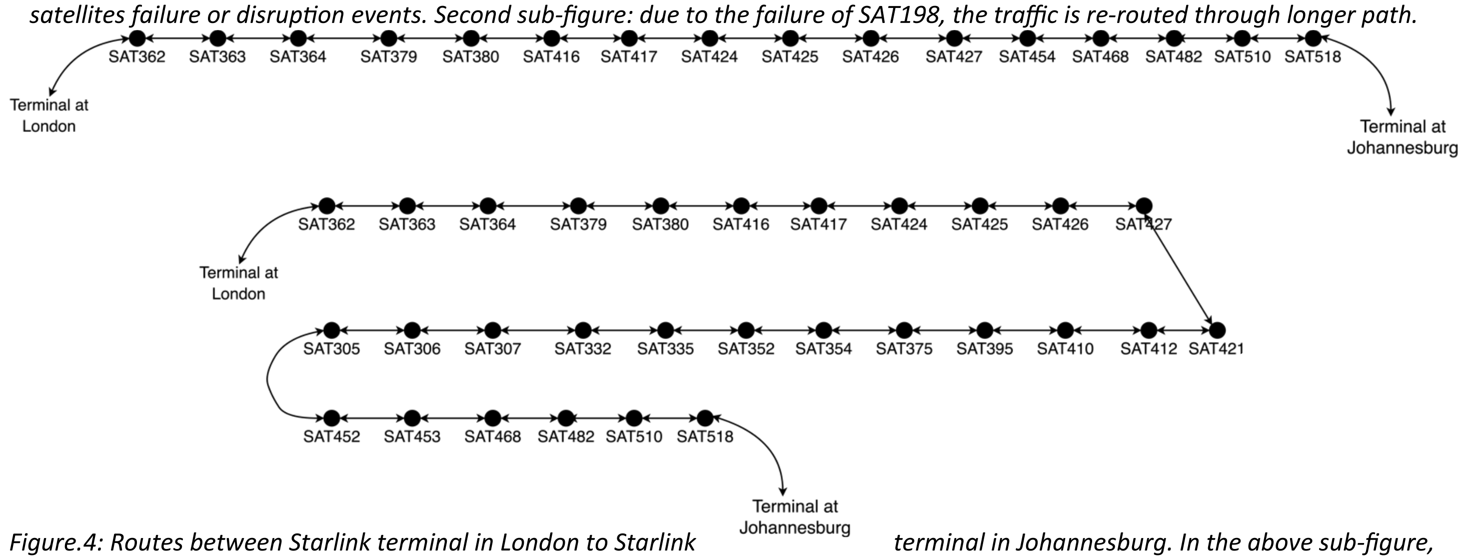

Figure.4: Routes between Starlink terminal in London to Starlink terminal in Johannesburg. In the above sub-figure, there is no satellites failure or disruption events. Second sub-figure: due to the failure of SAT454, the traffic is re-routed through longer path

In this second experiment, we studied how the network performance of Starlink mega-constellation will be affected by disruption event such as satellites failure. We measure the change of the network performance by (i) the change in the latency (i.e., round trip time), and (ii) the path-stretch due to re-routing the traffic away from the failed satellites.

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4.2.1. Experiment 2 – Measuring mega-constellation resilience – Results and Analysis:

- **Going from East to West:**
  In this scenario, we emulate a traffic from a Starlink terminal in Tokyo to another Starlink terminal in Los Angeles. As show in Fig.3 (top sub-figure), there are 7 hops between these two terminals in case of no satellite failures, and the average Ping RTT of this path is around 64 milliseconds. We then emulated a single satellite failure on this path between Tokyo and LA, specifically, SAT198, and measured the Ping RTT between these two terminals. As show in Fig.3 (bottom sub-figure), we observed a significant path-stretch between these two cities where the hop count jumps from 7 hops to 14 hops which severely affect the Ping RTT with new average latency of 169.7 milliseconds. We also observed around 3-4 seconds of packet drops which is due to the re-routing computational times
- **Going from North to South:**

  We repeat the same experiment but for different pair of terminals, specifically, between a terminal in London and another terminal in Johannesburg. First, we observe the higher number of hops between these two cities compared to the scenario where cities are located on East and West which gives some indications of how the satellite density are higher for high altitude compared to low altitude. Without any satellite failures, we observed 16 hop counts between London and Johannesburg (As shown in Fig.4, top sub-figure) with Ping RTT of 153.3 milliseconds. With random satellite failure on the path between these two cities (e.g., SAT454), we observed around 56% increase in the Ping RTT with an average latency of 240.2 milliseconds due to a path-stretch of 29 hops instead of 16 hops in case of no failures (as shown in Fig.4 bottom sub-figure).

5 Present and Foreseen TRL

The Mininet-based simulator is in TRL4 as it has been tested and validated in the lab environment and calibrated with real-world measurement data that we collected from Starlink terminal distributed across the globe. We currently explore the commercial opportunity through different programmes with the university and UKRI and the steps to develop it further in the TRL levels.

6 Exploitation, Dissemination and Communication Status

- We aim to eventually make the software simulator as an open-source for the research community to further develop and add different and advanced modules. As immediate next step after this project, we are hoping to work with the European Space Agency to enable wide community take up of the simulator/testbed.

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Updates: We are working on submitting this work in a top-tier peer-reviewed conference in the coming few months, and will make the source code available publicly on Github after that.

- We also aim to offer the hardware-in-the-loop part of the platform as a service for both industry and research communities to access to deploy and evaluate new protocols.

Updates: We are working on with the commercialisation office at the university of surrey to submit a proposal for market discovery programme that will allow us to explore the potential commercial opportunity of this platform as a service.

- The design principles and results of the proposed experiments will be published and demonstrated in peer-reviewed conference/journal papers

Updates: We have been published a post on Asia Pacific Network Information Centre (APNIC) about the measurement study we did as part of the calibration module of the LEO simulator/emulator. The article is available here. We also submitted a paper titled *"Network Testbed for Small Satellites (NeTSat) - Distributed Space Adaptive Communications and Security for Multi-Constellation Networks"* to American Institute of Aeronautics and Astronautics (AIAA) SciTech Forum and we are working on another peer-reviewed publication.

7 Impacts

Impact 1: Enhanced EU – US cooperation in Next Generation Internet, including policy cooperation.

The main objective of this collaboration is to facilitate the use of the two testbeds to the research communities in both US and Europe. Demonstrating this inter-connectivity between the two testbeds, and open-source the architecture and deployment model would allow our research groups across EU and US to replicate the same model, and enable further collaborations. Having a fully interconnected transatlantic testbed is also important for taking advantage of expected closer ties in EU-US R&D collaboration relating to Space Research and novel applications of 5G/6G, Autonomous Vehicles, and AI/ML over Starlink-like networks. And particularly for both teams at Surrey and VT, the collaboration on this project enabled both teams to work and collaborate on a further project beyond this NGI Atlantic project.

Impact 2: Reinforced collaboration and increased synergies between the Next Generation Internet and the US Internet programmes.

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Inter-connecting the two testbeds, making the simulator software open-source for the research community, and offering the testbeds as a service that will create the environment and empower the research community to work, collaborate and develop research ideas for the next generation internet.

As a result of this project, Dr. Jon Black and his team have recently secured research grant fund from the Commonwealth Cyber Initiative Southwest Virginia to address the cybersecurity challenges of inter- and intra-constellation communications of internet satellite constellations using the simulator and the across Atlantic testbed we developed during this project (please find more details here).

Impact 3: Developing interoperable solutions and joint demonstrators, contributions to standards.

The testbed with its connectivity across the Atlantic will give rise to step changes in the field because it will provide a distributed testbed that, at its heart, promotes interoperability, as it allows different mega-constellations with internal rules, e.g., different ground station-satellite association criteria, different internal routing to inter-connect. This will enable:

- Academics from a multidisciplinary research community of both networking and aerospace researchers to re-think and design new network protocols and constellation management mechanisms, creating a platform for new joint and interoperable systems design research papers and projects.
- Established players, hi-tech start-ups, as well as SMEs and “New-Space” companies to test and verify their new protocols on a high fidelity/accurate testbed before the expensive deployment phase on real-world satellites.

Impact 4: An EU - US ecosystem of top researchers, hi-tech start-ups / SMEs and Internet-related communities collaborating on the evolution of the Internet

One of the objectives of this project is to offer the two testbeds as a service to allow SMEs and start-ups to design and evaluate new network protocols in a realistic environment. We received high interests from different companies (e.g., CGI and Mangata Networks) to use this trans-Atlantic testbed to test and simulate their future scenarios before going to prototype implementation. We are also collaborating with Telefonica Research Barcelona and Microsoft Azure Space (via Microsoft Research) on the cloud/connectivity/networking aspects of our testbed. In our conversations with these companies, they have indicated that inter-constellation connectivity as well as a more principled way to think about failure and resilience will be critical features for their future plans and therefore forms the next step in our testbed roadmap.

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8 Conclusion and Future Work

Existing routing protocols such as OSPF cannot cope with the high dynamics of LEO network and the fast topology changes. Thus, one of the potential future works is to design and implement a pro-active routing protocol that predict the network topology changes and pre-compute satellites' routing tables ahead of time such that when the changes occur, the updated routing tables can be deployed instantaneously.

We also observed that topology design can play a vital role in how resilient the LEO network can be. We will be working on designing other experiments to understand how to design a resilient and robust network topologies for LEO networks.

9 References

10 Glossary

OSPF	Open Shortest Path First
R&D	Research and Development
ML	Machine Learning
AI	Artificial Intelligence
RTT	Round Trip Time

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Framework Programme of the European Union