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FIREMAN
(**F**ramework for the **I**dentification of **R**are **E**vents via **MA**chine learning and IoT **N**etworks)

Year 1 report (5.2019 – 4.2020)

1. Identification

Project Id	
CHIST-ERA Call topic	Big data and process modelling for smart industry (BDSI)
Project acronym	FIREMAN
Project title	**F**ramework for the **I**dentification of **R**are **E**vents via **MA**chine learning and IoT **N**etworks
Start date	May 2019
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Website	https://fireman-project.eu/

Coordinator of the project	
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2. Summary

The Internet of Things (IoT) is creating a new structure of awareness – a cybernetic one – upon physical processes. Industries of different kinds are expected to join soon this revolution, leading to the so-called Factories of the Future or Industry 4.0. Our considered IoT-based industrial cyber-physical system (CPS) works in three generic steps as presented in Figure 1:

1. **Large data acquisition / dissemination:** A physical process is monitored by sensors that pre-process the (assumed large) collected data and send the pre-processed information to an intelligent node (e.g. aggregator, central controller).
2. **Big data fusion:** The intelligent node uses machine learning techniques (e.g. data clustering, pattern recognition, neural networks) to convert the received ("big") data to useful information to guide short-term operational decisions related to the physical process.
3. **Big data analytics:** The physical process together with the acquisition and fusion steps can be virtualized, building then a cyber-physical process, whose dynamic performance can be analysed and optimized through visualization (if human intervention is available) or artificial intelligence (if the decisions are automatic) or a combination thereof.

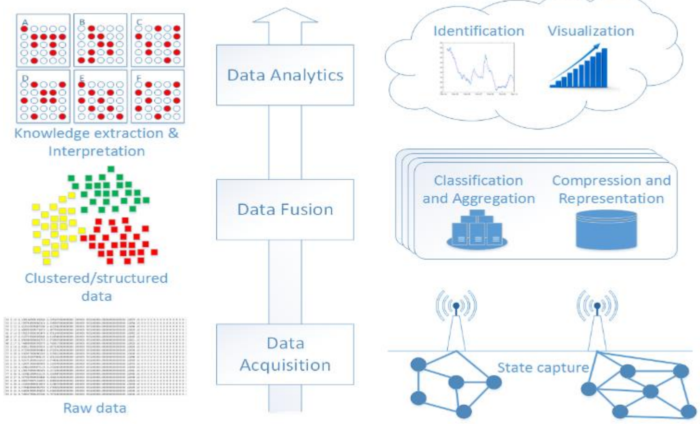


Figure 1: The FIREMAN approach and concept illustration

The **FIREMAN** focus is on how to optimize the prediction, detection and respective interventions of rare events in industrial processes based on these three steps. The framework is application-independent; however, our demonstrated solution will be designed case-by-case. We will consider the CPS working as a complex system so that these three steps, which operate with relative autonomy, are strongly interrelated. For example, the way the sensors measure the signal related to the physical process will affect what is the best data fusion algorithm, which in turn will generate a certain awareness of the physical process that will form the basis of the proposed data analytics procedure. This analysis of the three-layer model was motivated and initially tested in two smart grid cases.

In specific terms, we have proposed a general framework based on six general guiding questions that define the boundary conditions to provide ultra-reliable detection / prevention of rare events related to pre-determined industrial physical processes. We have initially identified several potential applications from SEAT at different industrial plants in Spain, and from different LUT University laboratories. Additionally, we have also worked with a well-known (simulation) benchmark scenario for anomaly detection in industrial processes called Tennessee Eastman Process (TEP) for testing purposes. For selected applications, we have provided a detailed description of anomalies and related Key Performance Indicators (KPIs); additionally, we have listed the communication system KPISs. We have also applied the proposed framework based on one plus six questions in three applications selected by LUT (TEP, a low-voltage DC microgrid and a welding machine).

For testing purposes, we started our research focusing on TEP, which consists of five major parts: a condenser, a vapor-liquid separator, a reactor, a product stripper, and a recycle compressor. It simulates a normal production process with twenty-one different faulty processes caused by some arbitrary/known disturbances. There are 52 monitoring variables, 41 measured and 11 manipulated. Once a faulty condition is activated, the dynamics of the process are affected, and some values may change. For FIREMAN, we consider that these 52 variables are signals during the acquisition phase. In this phase, those signals can be sampled in different manners: the most usual periodic sampling (get a sample at every specified period of time) or event-driven, non-periodic, sampling (get a sample always that a predetermined event happens, e.g., sample the signal whenever it is above or below a given threshold). Our results showed that this approach can significantly reduce the number of samples in the acquisition phase, which also impact the number of transmissions required. Different protocols for the event-driven approach were studied in more details in an electricity metering dataset with much lower granularity, showing excellent results in terms of data compression and reduction of traffic offered to the communication network.

The data transmission and dissemination from sensors to the storage/processing unit(s) relies on an IoT network. Initial results showed the potential of promising existing technologies based on Low-Power Wide-Area Networks (LPWAN) and future applications beyond 5G systems such as Non-Orthogonal Multiple Access (NOMA), massive multiple-input multiple-output (MIMO), Intelligent Reflective Surfaces (IRS), and grant-free random access. Multi-class ALOHA and Generalized Frequency Division Multiplexing (GFDM) were also evaluated. We have also analysed in a testbed the performance of a private industrial LTE network for one specific control application, leading to poor results due to high values of latency (from 20ms in the perfect scenario to more than 200ms with some network congestion). These results indicate the need for different solutions for Industrial IoT. In addition, we have also prepared a study of twenty-one factors to support the selection of the most suitable IoT platform based on the applications' needs.

For data fusion, we have also starting experiments with TEP. We have employed some classical methods for dimensionality reduction, such as the Principal Component Analysis (PCA) and mutual information. We have preliminary results in a wireless sensor network scenario considering a Graph Signal Processing technique to reduce the dataset dimensions. For the data analytics, we have proved based on another dataset the high performance of the Quantitative Association Rule Mining Algorithm (QARMA) for detecting rare events in industrial environments. For FIREMAN, QARMA is being tested to create association rules for TEP, trying to assess its performance against the existing solutions. The qualitative association rules could also be used in the data fusion since QARMA "tells" what variables are important in detecting anomalies. Additional work on QARMA is being carried out to classify faults in power grids.

The ongoing research based on TEP aims at incorporating all aspects together to assess the performance of the anomaly detection in that benchmark and compare the results with the existing literature in the field. Our work will employ a communication network layer following a model proposed in the literature (including aspects from physical layer and network layer, including advantages and drawbacks of cloud/edge computing in performing the computational tasks needed). We will also start tests in real environments at LUT and SEAT based on the insights obtained during the extensive study of TEP.

Our activities have already proved its impact within the academic community: we have organized a special session in a top conference, published several papers in top journals and conferences, and many other papers are currently under review. We are also applying to host a workshop in the prestigious IEEE PIMRC'20 in London. More than this, we expected that our results have impact beyond academia. For example, predictive maintenance may lead to economic benefits to industries due to improved efficiency in the plant with less downtimes. Besides, FIREMAN may help to reduce accidents in industrial environments. All in all, FIREMAN activities follow the concept of Industry 4.0, which is expected to be a source of a new wave of qualified jobs in Europe.

More details of FIREMAN (including deliverables and research papers) can be found in our website: https://fireman-project.eu/. Contact information: Pedro.Nardelli@lut.fi (project coordinator).

3. Progress Report

3.1. Project objectives and activities implemented

During the first periodic reporting phase of the project, i.e., from May 2019 (M1) to February 2020 (M10), three technical work packages (WPs) of FIREMAN have been active. In what follows, we provide a summary of the research activities implemented at WP level during this period.

WP2 aims to define the key requirements of the use cases to be studied, build a general framework for providing an ultra-reliable rare-event detection and understanding the fundamental limits of the proposed solutions. The general idea is presented in [C-3].

During Task 2.1 (led by **SEAT**), the focused study cases were defined, and key performance indicators (KPIs) were proposed. **SEAT** proposed a table to be filled with the support of experts in order to precisely identify the application KPIs. **SEAT** has applied the approach in different study cases: drive chain failure in paintshop processes and spindle (kind of actuator) failures in Computer Numerical Control (CNC) grinding machines in the machining centre. **LUT** applied in three cases: micro-grid, Tennessee Eastman Process (TEP) and a welding machine. **CTTC** and **UOULU** proposed a generic set of KPIs related to the wireless communication in industrial setups. As a side note, as previously discussed, the study cases from Nokia and the wind turbine needed to be dropped. **AIT** provided the technical coordination of this task. This task has been now finalised and the outcome is available in D2.1. In Task 2.2, **LUT** (task leader) further developed the 3-layer model of cyber-physical systems to focus on rare-event detection. The proposed framework is general but can be specified for all use cases studied in the context of FIREMAN (and beyond them). The framework is based on six questions, going from sensors to analytics, covering aspects related to the design of communication and choices in computing architecture. This approach was tested in the three **LUT** cases, supported by **UOULU** and **AIT**. **SEAT** studied their use cases following this approach. This task has been now finalised and the outcome is available in D2.2 and [S-2]. Task 2.3 has so far focused on analysing the performance limits of the Quantitative Association Rule Mining Algorithm (QARMA) in two controlled scenarios: (i) fault classification in power grids; and (ii) TEP anomaly detection and diagnosis. This task involved **AIT** (task leader) and **LUT**. **UOULU's** work involves the effect of communication networks on QARMA. The approach based on theoretical bounds was not relevant at this point, and we decided to focus on QARMA. For the future, we expect to analyse the theorical performance limits of QARMA and compare it with state-of-the-art approaches, like deep learning. When applicable, we can try to build the analysis based on Bonferroni bounds. Ongoing results are documented in [C-4], [S-2] and [S-9].

Based on the definition of requirements and system architecture in **WP2**, the overall aim of **WP3** is to design a data acquisition framework that encompasses all stages from local data collection and storage to data transmission in large-scale industrial deployments. Since August 2019 (M4), the research activities in **WP3** are focusing on the fulfilment of specific FIREMAN objectives, i.e.,

- Develop accurate analytical/simulation models for the signal characterization of the different industrial processes.
- Develop an agile, cost-efficient, network deployment, enabling seamless and secure connectivity for a sheer scale of sensors and local data collection.
- Design transmit-diversity schemes and optimize protocol operation to guarantee ultra-high reliability and low latency for mission-critical sensor data and control commands.

During the first months of **WP3**, the FIREMAN partners have already started contributing towards these objectives, e.g., data characterization (Task 3.1), local data collection (Task 3.2) and data transmission (Task 3.3). In Task 3.1, **LUT** has investigated different sampling strategies for data acquisition ([C-2]) while **CTTC** and **UOULU** have focused on the derivation of analytical models for traffic characterization based on point processes. In Task 3.2, **LUT** is considering the level of data compression required for periodic and event-driven sampling by considering the reconstruction error ([S-1]). **CTTC** has proposed a data compression strategy to effectively exploit the temporal and spatial correlation in the sensors' observations while **AIT** is investigating the trade-offs that arise when using standard relational database technology to manage the datasets required in FIREMAN versus using NoSQL databases. **AIT** is also exploring candidate database platforms which are suitable for the storage system of the FIREMAN architecture. Finally, in Task 3.3, the involved partners have been investigating potential technical enablers to accommodate large-scale data transmission. In this context, **LUT,** together with **AIT,** have studied the applicability of massive multiple-input multiple-output (MIMO) and non-orthogonal multiple access (NOMA) networks in dense industrial setups ([J-1], [J-3], [C-7], [C-11], [C-12]). **CTTC, LUT and AIT** have jointly investigated the potential of the Intelligent Reflective Surfaces (IRS) paradigm for enhancing reliability in ultra-reliable industrial scenarios ([C-9], [S-4]). **UOULU** has also investigated the performance of LoRa technology enhanced with a novel message replication strategy in highly dense industrial communication scenarios ([J-4], [C-10]). **LUT** also provided results of the performance of Generalized Frequency Division Multiplexing (GFDM) and multi-class ALOHA systems ([C-6], [C-13]). Moreover, they started investigating the impact of Successive Interference Cancellation (SIC) in LoRa networks and uplink superposed replications in Low-Power Wide-Area Networks (LPWAN) ([S-6], [S-7]). **SEAT** is preparing an internal report about their own existing data acquisition, communication and processing infrastructure to be used by the partners. Finally, **UOULU** investigated a multi-antenna scheme for wireless energy transfer for massive machine-type communication (mMTC) scenarios ([S-8]).

A detailed discussion on the **scientific achievements** per task level for the first year of FIREMAN is provided in Section 3.3 of the report. In addition, the **WP3** research outputs have been consolidated in numerous **scientific publications** which are listed in Section 4.1 of this report. Two FIREMAN **deliverables**, i.e., D3.1: "*Report on Physical Process Data Modelling*" and D3.2: "*Design and Functional Architecture for Data Acquisition*", are expected to be published in July 2020 (M15) where the main results of the **WP3** activities will be documented. Without significant deviations, **WP3** is so far progressing well according to the initial project plan and towards its objectives defined in the proposal. For Year 2 of FIREMAN, we are expecting the finalization of the activities in Tasks 3.1 and 3.2 with further insightful results and the development of additional technical components for Task 3.3. The level of partner collaboration in the context of **WP3** is high as demonstrated already by the multiple joint publications. The bi-weekly telcos organized by **CTTC** (**WP3** leader) provide useful status updates while the monthly reports uploaded in Sharepoint offer a regular overview of the partners' activities.

The goal of **WP4** is to develop advanced machine learning techniques to perform data fusion, mining, and interpretation, which will enable efficient control and awareness of the physical processes. These efforts will allow us to convert the pre-processed raw sensor data to useful information and enable the analysis and short-term operational decisions based on preliminary analysis. Since November 2019 (M7) the **WP4** activities on the evaluation of different ways to aggregate and cluster the heterogeneous data have started. These activities are related to Task 4.1. The involved partners (**UOULU, LUT, CTTC, AIT, SEAT**) have made significant progress. **UOULU** has started a literature review on clustering and data aggregation since November and has progressed a lot with the data aggregation and scheduling with QoS guarantees research. In January, **UOULU** started working on interference meta-distributions for MTC scenarios with data aggregation. **CTTC** is exploring various strategies for intra-cluster discovery and cluster-head selection policies to address the tradeoffs between energy-efficiency, cluster formation time and coverage. At the same time, **LUT** has been focusing on the communication aspects of system, with their work on Massive MIMO NOMA and grant-free random access, as well as GFDM and multi-class ALOHA. In December 2019 (M8), **UOULU** finished the initial modification on the Python LoRA Simulator and started comparing results from simulations and theoretical models. **SEAT** is currently collecting detailed information about their study cases to be further used by FIREMAN consortium. **TCD** as the **WP4** leader has been coordinating the activities and collecting the monthly reports on the active tasks. Task 4.2 starts in M12, and the planned activities include studying the applicability of data fusion based on Mutual Information and advanced machine learning algorithms.

3.2. *Transnational collaboration*

LUT and **AIT** have collaborated in a fault classification in power grids to compare the performance of QARMA and deep learning in a controlled task, related to Task 2.3. In relation to WP2 and WP3, **LUT**, **AIT** and **UOULU** are actively collaborating to study and assess the impact of event-driven approaches in different industrial settings based on the proposed three-layer model. In the context of WP3 and WP4 research activities, Dick Carrillo Melgarejo (**LUT**) performed a research visit at **CTTC** premises during November 2019 where he collaborated with Charalampos Kalalas (**CTTC**). The principal research topic (grant-free uplink access) was aligned with the objectives of Task 3.3. The joint research efforts and outcomes resulted in the preparation of a conference paper which was submitted in January 2020 and was accepted for presentation ([C-9]). Besides, **LUT** is also working with **AIT** in the topic of massive MIMO and NOMA related to WP3 and WP4 ([J-3], [S-4], [S-7]). Besides, **LUT** and **UOULU** (although in the same country) have also collaborated in tasks related to event-driven techniques, cyber-physical systems modelling and advanced communications ([J-5], [C-2]). **AIT**, **LUT** and **TCD** are currently working on TEP for dimensionality reduction. The whole team collaborate in two publications: [C-3] describing the general idea of FIREMAN and [S-2] presenting the first results related to TEP. Besides, **SEAT** was involved in the selection process of the researcher hired by **CTTC** who will be fully allocated in FIREMAN.

All in all, the different expertise of the consortium has been successfully channelled to solve the proposed interdisciplinary problem, as well as specific domain problems related to cyber-physical system modelling, data acquisition, fusion and analytics. This convergence has been very positive, making the team as a whole to solve problems that the groups would be hardly capable to solve individually.

As we keep frequent telcos (every second week for technical discussions, and monthly steering group) and target at concrete goals and action points, the transnational collaboration is going smoothly. The only obstacle is the lack of synchrony in the funding agencies, which make face-to-face meeting more difficult (see Section 3.7).

3.3. Significant events and results

The research of **WP2** is divided into three tasks: Two already concluded and one is ongoing. The ended tasks are related to the definition of potential study cases, their KPIs and the general framework to be tested in the particular study cases. The ongoing task focuses on fundamental limits. We hereby highlight the main technical achievements so far **per task level for each individual beneficiary involved**.

Task 2.1: Definition of Key Performance Indicators and Requirements (M1-M4; responsible: SEAT; involved: LUT, CTTC, AIT, UOULU). This task provided the KPIs and requirements to test and validate the proposed approach. **SEAT** defined a special table to be filled to define the KPIs, and filled it considering the following cases: drive chain failure in paintshop processes and spindle (kind of actuator) failures in Computer Numerical Control (CNC) grinding machines in the machining centre. **LUT** has redefined its study cases: TEP benchmark scenario, micro-grid and welding machine; it filled the proposed table. **CTTC** and **UOULU** worked together to define the communication KPIs for industrial environments under consideration. **AIT** provided the technical coordination of this task. The main outcomes of this task are documented in D2.1.

Task 2.2: Scenarios and System Architecture (M3-M6; responsible: LUT; involved: AIT, UOULU, SEAT). This task will develop a general framework based on a three-layer model constituted by physical, information and regulatory layers. **LUT** proposed a 3-layer model of industrial cyber-physical systems used to build a general framework based on 1+6 questions in a step-by-step procedure that give the boundary conditions of the particular solution to be taken. **LUT** tested this approach in its three proposed study-cases, also partly looking at potential use in electricity grids ([J-5], [S-3]) and selection of IoT platforms for ML ([S-5]). **SEAT** focused on its two test cases. **UOULU** and **AIT** provided support to **LUT** via several interactions in the proposed framework. The main results of this task are in D2.2 and in [S-2].

Task 2.3: Fundamental Studies (M5-M21; responsible: AIT, involved: LUT, UOULU). This task focuses on the analysis and research on theoretical bounds for our detection and prediction process according on the "important" events identified in Task 2.1. **AIT** focused on the use of QARMA algorithm in different scenarios ([C-4], [S-2]) in collaboration with **LUT** and **UOULU** and with focus on TEP; and in [S-9] in collaboration with **LUT** for fault classification in power grid scenarios. In particular terms, these results indicate the potential to use QARMA for rate-event detection; one remarkable issue here is that QARMA has a high level of explainability of outcomes.

The **WP3** research activities span over three different tasks which have all been initiated during the first year of the project. We hereby highlight the main technical achievements so far **per task level for each individual beneficiary involved**.

Task 3.1: Physical Process Data Modelling (active since August 2019 (M4); responsible: LUT; involved: CTTC, UOULU). The objective of this task is the characterization and classification of the raw and pre-processed data generated by the sensors. In this context, **LUT** (task leader) has investigated the differences between periodic and event-driven data sampling and has developed a flexible event-driven measurement technique based on spike-filtering. In addition, **LUT** has performed a classification of a power grid (electricity metering) dataset to identify which signals perform better with periodic or event-driven sampling and investigate whether the event-driven measurement technique with spike-filtering produces meaningful output for this dataset. Ongoing work by **LUT** aims at applying the proposed event-driven techniques in the TEP dataset with some preliminary results already obtained. **CTTC** has investigated analytical models for the accurate characterization of sensor traffic streams that exhibit high spatiotemporal correlation. Instrumental in this direction is the use of point processes, e.g., Markovian Arrival Process (MAP), which allow for a tractable expression of the traffic activation probability. The exact derivation of this metric will act as an input for the performance assessment of different communication protocols developed in Task 3.3 which rely on random access. The application of this framework has already been studied by **CTTC** for cascade failure modelling in an N-element power system using as datasets the operational (inter-failure) times of the electrical components. Several parameter-estimation strategies have been explored, i.e., method of moments, least squares, maximum likelihood, expectation-maximization algorithm, and the tradeoffs between complexity and accuracy have been identified. **UOULU** is also exploiting the MAP framework to model source arrivals at a given node.

Task 3.2: Local Data Collection and Storage (active since October 2019 (M6); responsible: AIT; involved: LUT, CTTC, SEAT). The objective of this task is the development of solutions for data collection and sampling and techniques for efficient data storage. In this context, **LUT** is studying the level of data compression required for periodic and event-driven sampling by considering the reconstruction error. A data compression strategy has been also developed by **CTTC** to effectively exploit the temporal and spatial correlation in the sensors' observations. The proposed strategy is composed of two building blocks: (i) an estimation block and (ii) a compression block. In the former, the temporal and spatial correlation of the data is exploited by means of a multidimensional linear filter in order to remove the impact of the sampling noise. In the compression block, the output of the estimation block is compressed by using truncated versions of the Karhunen-Loève expansions of the signals. **AIT** (task leader) is investigating the trade-offs that arise when using standard relational database technology (e.g., using Oracle 18c or MySQL 5.7) to manage the datasets required in FIREMAN versus using NoSQL databases, as it is well-known that the two general approaches can have significant implications on the ability of the project to handle big data. It is currently estimated (given datasets gathered and processed in the EU-funded projects PROPHESY and QU4LITY) that the size of the datasets required by FIREMAN will be in the order of 100MB at minimum to 10GB maximum, spanning 2 orders of magnitude in size difference. Already, working with the "educational" TEP dataset, the size of the data is around 100 MB (when expanded to include extra variables indicating state at previous times.) Even at maximum (10 GB), such dataset sizes are easily handled by traditional RDBMS technology, so Oracle 18c RDBMS should be an excellent candidate. However, depending on the access patterns required by the algorithms to be researched in FIREMAN, NoSQL databases supporting much higher CRUD operations throughputs, such as MongoDB are also valid candidates. In particular, since highly complex ad-hoc queries are not anticipated by the machine-learning algorithms to be used in the project, MongoDB, with its replication, sharding, and map-reduce server capabilities is also an excellent candidate as the storage system of the FIREMAN architecture. **SEAT** is collecting detailed information on how data are currently collected and stored in internal systems including data sampling and compression, and other relevant techniques and parameters. This information will be useful for **AIT** and **LUT** to determine the most suitable approaches for local data collection and storage considering a real industrial environment such as that of **SEAT**.

Task 3.3: Large-scale Data Transmission (active since November 2019 (M7); responsible: CTTC; involved: LUT, AIT, UOULU). The objective of this task is the design of agile communication schemes able to achieve scalable and ultra-reliable, low latency transmission of the sensing information. The ever-increasing number of interconnected devices expected in future industrial IoT applications will impose even more demanding requirements on the communication networks that will quickly surpass the capabilities of current technologies. Massive access, ultra-low latency, and high reliability are just a few of the features required to be provided by future communication systems. In this context, **LUT** has already extensively investigated the performance of massive MIMO-NOMA networks in dense industrial deployments ([J-1], [J-3], [C-7], [C-11], [C-12], [S-7]). **LUT** also studied a multi-class communication system based on ALOHA [J-2], the performance of GFDM modulation, which can be a promising solution for large-scale transmissions [C-6, C-13], and a preliminary demonstration of a 4G network in an industrial environment [C-1]. **LUT** and **CTTC** (task leader) have jointly studied ([C-9]) the applicability of the emerging IRS paradigm for reliable uplink access in an industrial scenario involving ultra-reliable low-latency communication (URLLC). The performance assessment revealed significant gains in terms of reliability, resource efficiency, and capacity and for different configurations of the IRS properties, unveiling the potential of IRS as a promising and low-cost solution to provide link diversity and achieve reliable uplink connectivity in industrial setups. **CTTC** has also proposed a general data-acquisition model composed of a fusion centre and N sensors where the impact of imperfect communication is considered ([S-2]). Using an ON-OFF power allocation strategy for a subset of active sensors, the transmission threshold is determined in such a way that the expected distortion of the best linear unbiased estimator at the fusion centre is minimized with respect to the channel realizations and the number of active sensors. **AIT** focuses on an mMTC scenario, where many power-limited sensor nodes, equipped with a single antenna, need to transmit their data to a hub (base station) with a high computational power and with an antenna array. The framework under study aims to maximize the sum rate of all transmitting sensors, subject to individual power and rate constraints. **UOULU** has already investigated the applicability of Long Range (LoRa) networks in highly dense industrial communication scenarios. The capacity of LoRa Wide-Area Network (LoRaWAN) in terms of the number of sensors under coverage has been evaluated using message replication techniques to exploit time diversity and increase reliability. In particular, a novel hybrid coded message replication scheme has been proposed by **UOULU** ([J-4]) which interleaves simple repetition and a recently proposed coded replication method and achieves improved performance - subject to minimum reliability requirements - without requiring additional transmit power. Moreover, they investigated the reliability gain when using superposed signal decoding at the gateways ([S-6]). In addition, **UOULU** has setup a system-level simulator of LoRa technology for testing various protocol solutions in the context of FIREMAN ([C-10]).

The work on **WP4** has started on time - November 2019 (M7). All partners involved in **WP4** have been taking part of the regular biweekly meetings related to the activities that are part of **WP3** and **WP2**. The purpose of these meetings is to keep the work harmonized between the tasks and to strengthen the collaboration between the partners. The participation in these meetings helped accelerate the activities related to **WP4**.

Task 4.1: Aggregation of heterogeneous big data (active since November 2019 (M7); responsible: UOULU; involved: LUT, CTTC, AIT, SEAT). The objective of this task is to enhance traditional clustering algorithms so that they account for the communication capabilities (e.g., limited communication infrastructure or provisionally deployed access points). The work on this task resulted in some early work delivered by **UOULU** and **LUT. UOULU** finished the work related to enhanced reliability in Low-Power Wide-Area Networks (LPWAN), in particular in LoRaWAN, with coded replications in November and started working on the data aggregation and scheduling with QoS guarantees, as well as the work on NOMA for enhanced ultra-reliable low-latency communications (URLLC) in coexistence with Enhanced Mobile Broadband (eMBB) traffic. This work resulted in a couple publications ([J-4], [S-6]). Their work on LPWAN [C10] will be presented at 6G Summit 2020. Also, **UOULU** is working on interference modelling in MTC scenarios with aggregation. **LUT** started the work on grant-free random access in collaboration with **CTTC**, which was accepted to the 6G Summit 2020 [C-9]. **LUT** is also extensively studying massive MIMO – NOMA scenarios ([J-1], [J-3], [C-7], [C-11], [C-12], [S-7]). **LUT** has also started work on spectral and energy efficiency in IRS-NOMA also together with **AIT** ([S-4]).

The first task in which **TCD** is involved starts in April 2020, but the discussions during the biweekly meetings allowed them to get a head start on some of the research that is planned in Task 4.2. This resulted in a journal paper that was accepted in the IEEE Systems Journal [J-6].

3.4. Technology readiness level (TRL)

FIREMAN is mainly located in TRLs 2 and 3. However, for some activities, like study of beyond 5G systems, FIREMAN is TRL 1. Applications to be studied at LUT and SEAT can be associated with TRLs 4 and 5.

3.5. Consortium meetings

Meetings*

N°	Date	Location	Attending partners	Purpose
1	May 17, 2019	LUT University	ALL	Online kickoff
2	Aug. 29, 2019	Oulu University	ALL	Kick-off and special session at ISWCS
3	May 15	Online	ALL (expected)	Yearly workshop

* All face-to-face meetings are canceled until COVID-19 situation becomes solved.

3.6. Deliverables

Deliverables*

N°	Title	Nature	Delivery date (month)		Partner in charge
			Contractual	**Actual**	
7.1	Website	Dissemination	M2	M1	CTTC
7.2	Plans for Dissemination, Communication and Standardisation	Dissemination	M3	M2	TCD
1.1	Quality Assurance Plan	Management	M4	M3	LUT
2.1	User requirements and key performance indicators	Research	M4	M4	SEAT
1.2	Data Management Plan	Management	M6	M6	AIT
2.2	System architecture design	Research	M6	M4	LUT
1.3a	Yearly report	Management	M12	M12	LUT
7.4	Draft exploitation plan	Dissemination	M12	M12	SEAT
2.3	Important Rare Events Identification	Research	M12	M12	AIT

*Available in the website. D2.2 will be updated when SEAT allows to publicly upload more detailed internal information related to test cases.

4. Documentation of results, valorisation, impact

4.1. *Scientific publications (conferences/workshops, book chapters, etc.)*

Scientific publications			
Publication Id		**Multi-partners (Yes/No)**	**International* (Yes/No)**
Journals			
[J-6]	M. Dzaferagic, N. McBride, R. Thomas, I. Macaluso, N. Marchetti, "*Improving In-Network Computing in IoT Through Degeneracy*", IEEE Systems Journal, February 2020.	No	Yes
[J-5]	M. Tomé, P. Nardelli, H. Majid Hussain, S. Wahid, A. Narayanan, "*A Cyber-Physical Residential Energy Management System via Virtualized Packets*", MDPI Energies, 13(3), 699, February 2020.	Yes	Yes
[J-4]	J. M. S. Sant'Ana, A. S. Hoeller, R. D. Souza, S. Montejo-Sanchez, H. Alves and M. De Noronha Neto, "*Hybrid Coded Replication in LoRa Networks*," IEEE Transactions on Industrial Informatics, January 2020.	No	Yes
[J-3]	A. S. de Sena, D. Benevides da Costa, Z. Ding, P. Nardelli, U. S. Dias, C. B. Papadias,"*Massive MIMO-NOMA Networks with Successive Sub-Array Activation*", IEEE Transactions on Wireless Communications, December 2019.	Yes	Yes
[J-2]	P. Dester, P. Cardieri, P. Nardelli, J. M. C. Brito, "*Performance Analysis and Optimization of a N-class Bipolar Network*", IEEE Access, September 2019.	No	Yes
[J-1]	A. S. Sena, D. Benevides da Costa, Z.Ding, and P. Nardelli, "*Massive MIMO–NOMA Networks With Multi-Polarized Antennas*", IEEE Transactions on Wireless Communications, September 2019.	No	Yes
Conference proceedings			
[C-13]	D. Carrillo-Melgarejo, S. Kumar, G. Fraidenraich, P. Nardelli, D. Benevides da Costa, "*Achievable Sum Rate and Outage Capacity of GFDM Systems with MMSE Receivers*", accepted to International Conference on Communications (ICC), Dublin, Ireland, June 2020.	No	Yes
[C-12]	A. S. de Sena, F. R. M. Lima, D. Benevides da Costa, and P. Nardelli, "*Enhancing User Fairness in Massive MIMO-NOMA Networks*", accepted to International Conference on Communications (ICC), Dublin, Ireland, June 2020.	No	Yes
[C-11]	A. S. de Sena, D. Benevides da Costa, Z. Ding, P. Nardelli, U. S. Dias, C. B. Papadias, "*Successive Sub-Array Activation for Massive MIMO-NOMA Networks*", accepted to International Conference on Communications (ICC), Dublin, Ireland, June 2020.	Yes	Yes
[C-10]	A. S. Hoeller, J. M. S. Sant'Ana, J. Markkula, K. Mikhaylov, R. D. Souza, H. Alves, "*Beyond 5G Low-Power Wide-Area Networks: A LoRaWAN Suitability Study*", 6G Wireless Summit 2020 (6G Summit), Levi, Finland, March 2020.	No	Yes
[C-9]	D. Carrillo-Melgarejo, C. Kalalas, A. S. Sena, P. Nardelli and G. Fraidenraich, "*Reconfigurable Intelligent Surface-Aided Grant-Free Access for Uplink URLLC,*" 6G Wireless Summit 2020 (6G Summit), Levi, Finland, March 2020.	Yes	Yes
[C-8]	C. Kalalas and J. Alonso-Zarate, "*Massive Connectivity in 5G and Beyond: Technical Enablers for the Energy and Automotive Verticals,*" 6G Wireless Summit 2020 (6G Summit), Levi, Finland, March 2020.	No	Yes

[C-7]	A. S. Sena, D. Benevides da Costa, Z. Ding, and P. Nardelli, "*Massive MIMO-NOMA Networks with Multi-Polarized Antennas*", in Proc. of IEEE Global Communications Conference (GLOBECOM '19), Hawaii, USA, December 2019.	No	Yes
[C-6]	D. Carrillo-Melgarejo, J. M. Moualeu, P. Nardelli, G. Fraidenraich, and D. B. da Costa, "*GFDM-Based Cooperative Relaying Networks with Wireless Energy Harvesting*", in Proc. of International Symposium on Wireless Communication Systems 2019 (ISWCS '19), Oulu, Finland, August 2019.	No	Yes
[C-5]	A. Chiumento, N. Marchetti, I. Macaluso, "*Energy Efficient WSN: a Cross-layer Graph Signal Processing Solution to Information Redundancy*", in Proc. of International Symposium on Wireless Communication Systems 2019 (ISWCS '19), Special Session on IoT in Energy Systems and Industrial Environments, Oulu, Finland, August 2019.	No	Yes
[C-4]	I. Christou, "*Avoid mistaking the hay for the needle in the stack: Improving Rare Event Detection with Online Pruning of Useless Rules in Quantitative Association Rule Mining*", in Proc. of International Symposium on Wireless Communication Systems 2019 (ISWCS '19), Special Session on IoT in Energy Systems and Industrial Environments, Oulu, Finland, August 2019.	No	Yes
[C-3]	P. Nardelli, C. Papadias, C. Kalalas, H. Alves, I. Christou, I. Macaluso, N. Marchetti, R. Palacios, J. Alonso-Zarate, "*Framework for the Identification of Rare Events via Machine Learning and IoT Networks*", in Proc. of International Symposium on Wireless Communication Systems 2019 (ISWCS '19), Special Session on IoT in Energy Systems and Industrial Environments, Oulu, Finland, August 2019.	Yes	Yes
[C-2]	M. Tomé, P. Nardelli, L. C. Pereira da Silva, "*Flexible event-driven measurement technique for electricity metering with filtering*", in Proc. of IEEE International Conference on Industrial Informatics (INDIN' 19), Espoo, Finland, July 2019.	Yes	Yes
[C-1]	F. Polunin, D. Carrillo Melgarejo, T. Lindh, A. Pinomaa, P. Nardelli and O. Pyrhonen, "*Demonstrating the Impact of LTE Communication Latency for Industrial Applications*", in Proc. of IEEE International Conference on Industrial Informatics (INDIN' 19), Espoo, Finland, July 2019.	No	Yes
Submitted papers			
[S-9]	D. Gutierrez-Rojas, D. Dantas, I. T. Christou, A. Nayaran, P. Nardelli, "*Deep-learning-based Fault Selection in Double-circuit Transmission Lines*", submitted to Industrial CPS conference, February 2020.	Yes	Yes
[S-8]	O. L. A. López, S. Montejo-Sánchez, R. D. Souza, C. B. Papadias, H. Alves, "*On CSI-free Multi-Antenna Schemes for Massive Wireless Energy Transfer*", submitted to IEEE Internet of Things Journal, February 2020.	Yes	Yes
[S-7]	A. S. de Sena, F. R. M. Lima, D. Benevides da Costa, Z. Ding, P. Nardelli, U. S. Dias, C. B. Papadias, "*Massive MIMO-NOMA Networks with Imperfect SIC: Design and Fairness Enhancement*", submitted to IEEE Transactions on Wireless Communications, February 2020.	Yes	Yes
[S-6]	J. M. S. Sant'Ana, A. S. Hoeller, R. D. Souza, S. Montejo-Sanchez, H. Alves, "*LoRa Performance Analysis with Superposed Signal Decoding*", submitted to IEEE Wireless Communications Letters, February 2020.	No	Yes
[S-5]	M. Ullah, P. Nardelli, A. Wolff, K. Smolander, "*Twenty-one key factors to choose an IoT platform*", submitted to IEEE Internet of Things Journal, February 2020 (major revision).	No	Yes

[S-4]	A. S. de Sena, D. Carrillo, F. Fang, P. Nardelli, D. B. da Costa, U. S. Dias, Z. Ding, C. B. Papadias, W. Saad, "*What Role Do Intelligent Reflecting Surfaces Play in Non-Orthogonal Multiple Access?*", submitted to IEEE Wireless Communication Magazine, February 2020.	Yes	Yes
[S-3]	H. Majid Hussain and P. Nardelli, "*IoT-based Heuristics for Demand Response based on Home Energy Management System*", submitted to Industrial CPS conference, February 2020.	No	Yes
[S-2]	D. Gutierrez-Rojas, M. Ullah, I. T. Christou, G. Almeida, P. Nardelli, D. Carrillo, J. M. S. Sant'Ana, H. Alves, M. Dzaferagic, A. Chiumento, C. Kalalas, "*Three-layer Approach to Detect Anomalies in Industrial Environments based on Machine Learning*", submitted to Industrial CPS conference, February 2020.	Yes	Yes
[S-1]	M. Tomé, P. Nardelli, L. C. Pereira da Silva, "*Distributed Event-driven Approach for Data Compression in Electricity Metering Application*", December 2019	Yes	Yes

*With the term "International", we refer to journals/conference proceedings with a content of cross-national significance and global soundness, beyond the context of a single country.

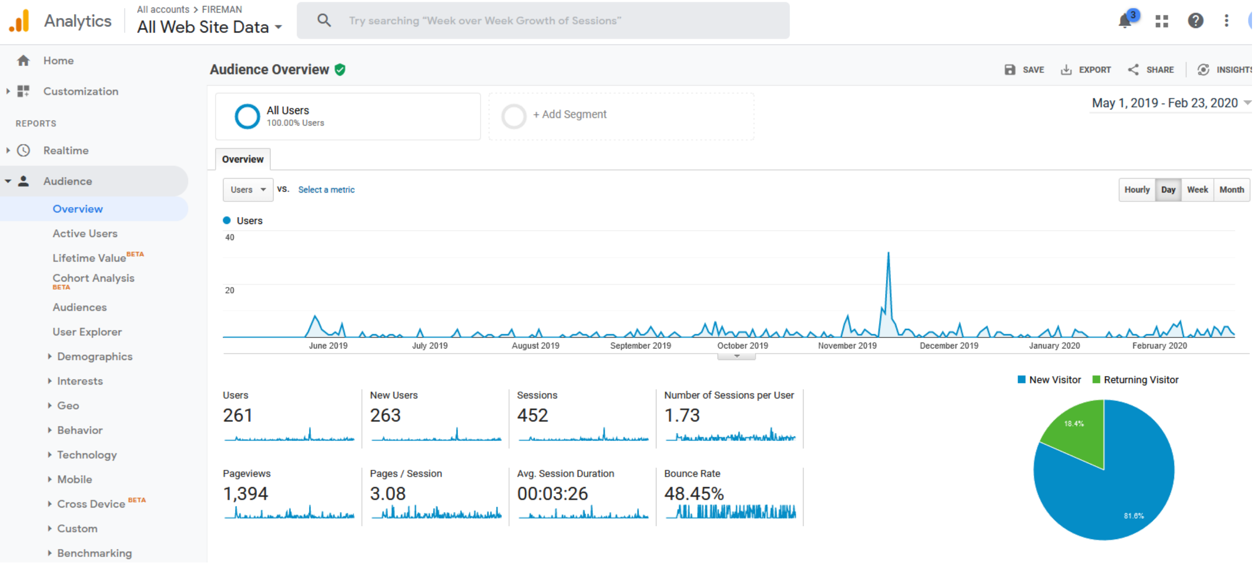
4.2. Valorisation (software, products, spin-offs, etc.)

TCD has been working on creating a spin-off company based on the machine learning research they are involved in. They successfully finished two commercialisation training camps organized by the NDRC (National Digital Research Centre). These two programs resulted in the **TCD** team winning two prizes related to the potential of the start-up idea and the commercial roadmap. Through the work related to the commercialisation of their research they have done a thorough customer discovery and validation, which resulted in a complete market and competitor analysis, and allowed them to clearly state the value proposition. Currently, they are preparing an application for commercialisation funding from Enterprise Ireland to continue the business and technology development which should result in a Minimum Viable Product (MVP) and first paying customers (early adopters).

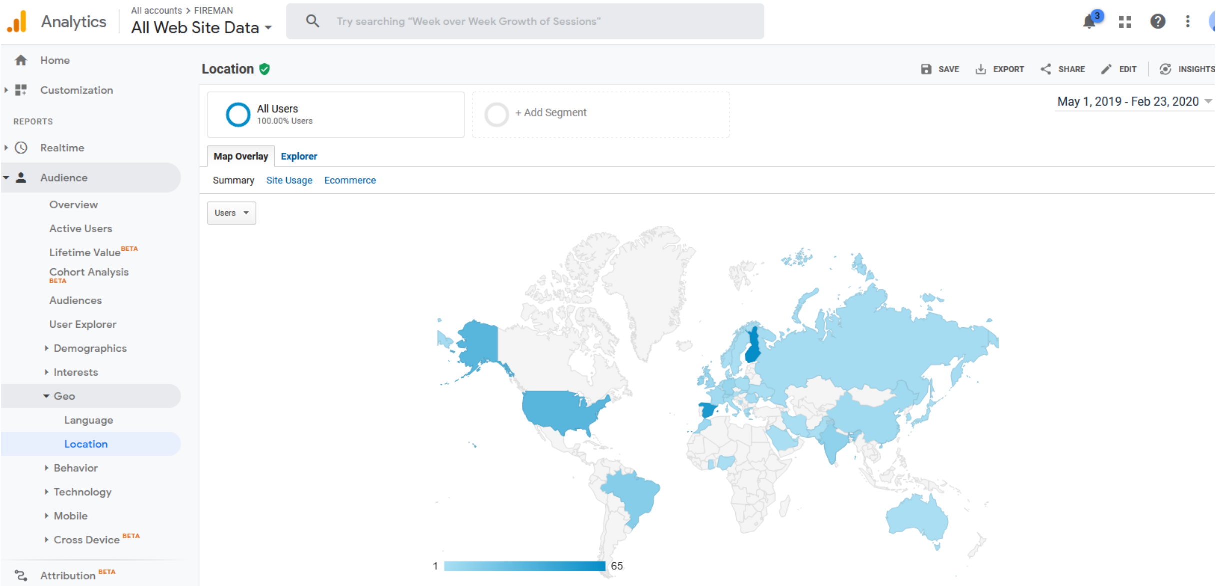
Open repository of FIREMAN: https://github.com/5uperpalo/FIREMAN-project

4.3. *Other dissemination of results*

- **Project website:** including deliverables, dissemination and events. **CTTC** is managing the website, including updates related to publications and events. According to Google Analytics (data retrieved on February 23th 2020), the FIREMAN website (https://fireman-project.eu/) has attracted worldwide interest since its creation.



Users 261
New Users 263
Sessions 452
Number of Sessions per User 1.73
Pageviews 1,394
Pages / Session 3.08
Avg. Session Duration 00:03:26
Bounce Rate 48.45%



- Organization of a special session in the prestigious ISWCS'19 conference with 3 papers from FIREMAN.
- Proposal of a workshop to IEEE PIRMC'20, where the FIREMAN team is organizing.
- SEAT presented the project internally in different committees both at the management level and at the operational level.
- The project coordinator presented FIREMAN in the 2019 EU-US Frontiers of Engineering Symposium in Sweden (https://www.naefrontiers.org/188386/2019-EUUS-Frontiers-of-Engineering-Symposium)