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Aggregate Processes as Distributed Adaptive Services for the Industrial Internet of Things

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Abstract

The Industrial Internet of Things (IIoT) promises to bring many benefits, including increased productivity, reduced costs, and increased safety to new generation manufacturing plants. The main ingredients of IIoT are the connected, communicating devices directly located in the workshop floor (far edge devices), as well as edge gateways that connect such devices to the Internet and, in particular, to cloud servers. The field of Edge Computing advocates that keeping computations as close as possible to the sources of data can be an effective means of reducing latency, preserving privacy, and improve the overall efficiency of the system. However, building systems where (far) edge and cloud nodes cooperate is quite challenging. In the present work we propose the adoption of the Aggregate Programming (AP) paradigm (and, in particular, the “aggregate process” construct) as a way to simplify building distributed, intelligent services at the far edge of an IIoT architecture. We demonstrate the feasibility and efficacy of the approach with simulated experiments on FCPP (a C++ library for AP), and with some basic experiments on physical IIoT boards running an ad-hoc porting of FCPP.

Keywords: Aggregate Programming, Field Calculus, Edge Computing

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1. Introduction

The Industrial Internet of Things (IIoT), namely the concepts and technologies of IoT applied to (smart) industry, is gaining increasing interest as it promises to improve productivity and safety in the workplace through the collection, analysis and exploitation of large amounts of data from the workshop floor. While there is no single definition of IIoT, the following one (taken from [1]) can be a useful reference for our purposes: “IIoT is the network of intelligent and highly connected industrial components that are deployed to achieve high production rate with reduced operational costs through real-time monitoring, efficient management and controlling of industrial processes, assets and operational time.”

From this definition we can deduce that connectivity and data collection are the main enabling elements of the IIoT. Furthermore, the reference architectures of the IIoT also stress the need of accessing high performance computational and storage nodes at a higher level, usually in the cloud. Again, we find several slightly different definitions of the IIoT architecture (see, e.g., [1, 2]); all of which, however, share most aspects with the one depicted in Figure 1.

We further partition the bottom layer in the figure into two sublayers: the *Far Edge* layer which contains the connected devices in the workshop floor, including: machines, sensors, actuators, real-time controllers, Human-Machine-Interface (HMI) units; and the *Edge gateways* that act as bridges towards the outside world. Then, the information collected by the gateways crosses the *Network* layer to reach the *Cloud* layer, where it is processed by rich applications for analysis, planning, optimization, etc. Of course the flow can also be reversed, so that plans and decisions created at the *Cloud* layer can reach the *Far Edge*.

A well known potential problem with this scheme is that pushing all the high-level functions to the cloud (i.e., far from the workshop floor), may have a negative impact on the reliability, cost, scalability and latency of the system. The field of *edge computing* aims at addressing the problem by moving some computations closer to the edge, notably moving (part of) the data processing

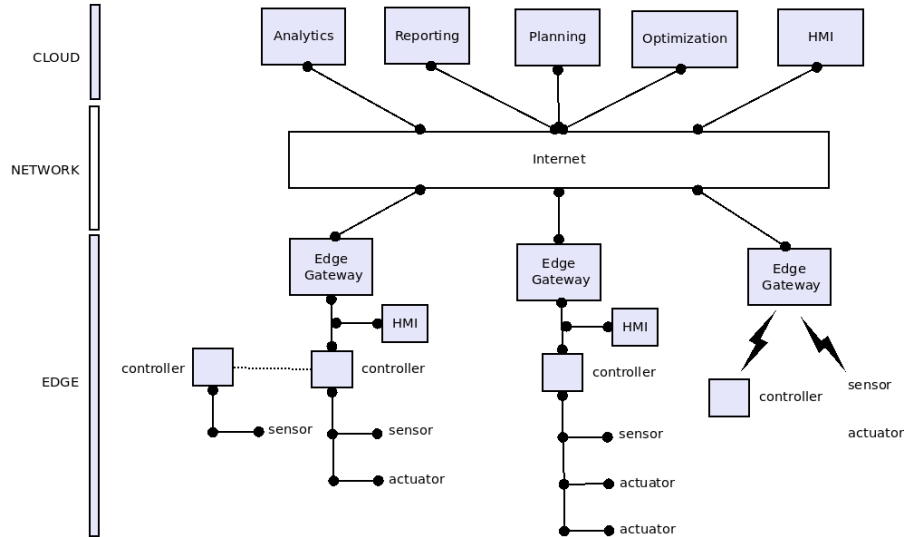


Figure 1: Reference Architecture of the IIoT.

closer to where the data is produced (see Figure 2).¹ The term *edge computing* does not prescribe exactly how close to the *things* (i.e., devices) the computation should be moved, and how much powerful should be the edge computing nodes. Thus, referring to Figure 1, the term can be applied to all the following (and quite diverse) situations: computations running in servers in the *Network* layer
 35 that are only a few hops from the *Edge Gateways*; computations running in the *Edge Gateways* themselves; and computations running in the *Far Edge* layer, exploiting the constrained memory and computing capabilities of smart devices. Overall, the pros and cons of moving the computation from the cloud towards the
 40 edge depend on the specific application scenarios. For instance, in the presence of fast and reliable internet connectivity, the intrinsic delay of a cloud-based

¹C.f. the presentation of the Horizon Europe Destination 3: Call ‘World leading data and computing technologies 2022’ given by Jan Comar at the Horizon Europe Cluster 4 - Digital, Industry & Space Info Day 2021 (https://ec.europa.eu/info/research-and-innovation/events/upcoming-events/horizon-europe-info-days/cluster-4_en), which can be found at <https://www.youtube.com/watch?v=SevWyhwaEwE>.

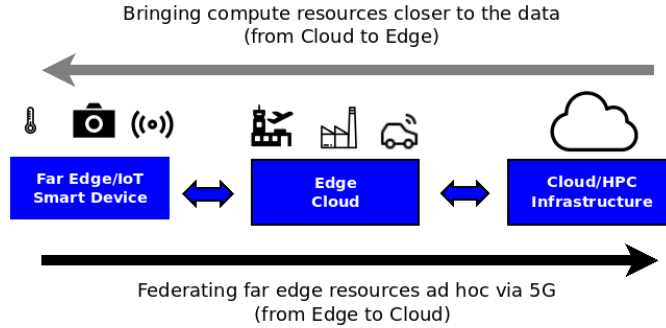


Figure 2: Cloud-Edge-IoT Orchestration.

solution may actually be very tiny. Moreover, in some application scenarios, issues and dangers related to scalability and reliability of edge-based solutions may arise.

45 In this paper we shall focus on the latter meaning of edge computation given above, whereby offloading some of the computations to the *Far Edge* layer can make them more robust, adaptive and responsive. In particular, we propose an approach that makes it possible to build distributed services for the IIoT running on highly resource-constrained devices. At the core of our approach

50 lies the possibility of running distributed computations on IIoT devices by relying on the FCCP library, a C++ implementation of Field Calculus (FC) [3]. Such computations are defined as processes in the Aggregate Programming (AP) paradigm [4], and in the foundation of this paradigm provided by the Field Calculus (FC) [5]. Aggregate Programming is suitable for programming networks of

55 devices forming an open dynamic topology with gossip-based communication. In the IIoT settings, this covers the devices at the *Far Edge* layer including in particular mobile devices, such as wearables carried by workers, or sensors attached to machines and objects that move, such as forklifts and pallets.

The main contributions of this paper are as follows:

- 60
1. we extend the FCCP library with the `spawn` construct enabling *aggregate processes*;
 2. we port the extended FCCP library to a resource constrained, IoT physical DecaWave board, equipped with the Contiki NG operating system;

3. we identify an IIoT use case that can be addressed by applying the AP
65 paradigm to program a network of devices equipped with FCPP;
4. we provide simulations of this IIoT use case; and
5. we provide preliminary experiments with physical DecaWave boards run-
ning FCPP.

The paper is structured as follows. Section 2 reviews related work. Sec-
70 tion 3 briefly recalls AP and its FCCP implementation [3], which is a library
providing FC as a C++ internal Domain-Specific Language (DSL). Section 4
describes the fundamental step of porting the FCPP library on a DecaWave
board, which provides wireless communication on a resource constrained System
on Chip (SOC). Section 5 links the powerful constructs of FC to some types
75 of services that can be implemented in an IIoT setting. Section 6 describes an
IIoT scenario of a *Warehouse App*, an AP service running on hardware with the
physical characteristics of the DecaWave board; then simulates its operation
through the FCPP 3D simulator, and presents preliminary experiments with
physical DecaWave boards running a port of the FCPP library. Finally, section
80 7 concludes the paper discussing further research directions.

2. Related Work

2.1. Edge Computing in the IIoT

As stated in the introduction above, the present paper focuses on a method
for exploiting the edge layer of the IIoT. In [6], the authors propose an in-
85 teresting survey about the applications, architectures and challenges that arise
in IIoT edge computing. They envision potential benefits of edge comput-
ing in: reducing the decision-making latency; saving bandwidth resources to
some extent; protecting privacy; reducing operational costs. Applications that
can exploit these benefits include prognostics and health management (PHM),
90 manufacturing coordination, and smart logistics. Compared to classic Internet
of Things (IoT), IIoT has some peculiar characteristics where edge can shine:
deployment scale of sensors is very large, with high precision requirements and

low tolerance for delay. An assumption that may hold in IIoT is that a high rate of nodes have fixed positions, as opposed to, e.g., IoT applications based
95 on mobile phones and wearables. In the present paper, as we shall see, we do not make this assumption, relying on the built-in ability of AP to smoothly deal with mobile nodes; this opens the way to IIoTs with important components provided by user devices and other mobile equipments. According to the survey, the typical tasks executed at the edge consist of (one or more of) the following
100 three steps:

1. local preprocessing of source data,
2. make some immediate decisions,
3. upload computed decisions or preprocessed data to the cloud.

Note that, beside data preprocessing, it is possible to make local decisions in a
105 edge device.

Some reference architectures (RA) for edge computing in IIoT are reviewed in [7]. The Far Edge architecture presented in an H2020 project [8] proposes to include a ledger in the edge layer, for providing security. The Edge Computing 2.0 RA proposed by the Edge Computing Consortium (ECC) stresses the
110 organization of IIoT applications as interacting services. The RA architecture proposed by the Industrial Internet Consortium assumes the presence of a proximity network at the edge layer. All of the RAs reviewed in [7] are designed following the ISO/IEC/IEEE 42010:2011 software engineering standard [9].

While Data Management is a fundamental task that can be partially off-
115 loaded to the edge layer (and thus we shall consider the related literature in the dedicated section 2.2), other tasks, regarding decision and control are also relevant.

In [10], a monitoring system is implemented at the edge layer, by programming data acquisition and predefined detection mechanisms on an FPGA unit.
120 The authors point out that the operation of power systems is extremely time-critical, and low-latency communication needs to be considered for most control and monitoring applications. Thus, an IIoT solution deployed on the workshop

floor is needed.

In [11], the authors propose a *cognitive layer* just on top of the physical de-
125 vices, with responsibilities of data classification, test setting, test run condition
processing, alarm information processing, and data report generation. More-
over, exploiting Finite State Machine (FSM) models and fuzzy algorithms, the
layer is able to perform working mode matching, determination and switching.

In [12], a Mobile Edge Cloud (MEC) architecture is proposed for robot
130 control in industrial automation. The MEC is a network architecture concept
that offers a cloud-like capability at the edge of the network, and being close
to the controlled devices decreases the latency and increases the performance of
high-bandwidth applications.

2.2. Distributed Data Management

135 Distributed Data Management, which involves generating, aggregating, stor-
ing, analysing and requesting data, is one of the main kinds of tasks that AP-
powered IIoT edge devices can perform, and that will be discussed in the present
paper.

In [13], the authors survey approaches to distributed data aggregation, men-
140 tioning Wireless Sensor Networks (WSN) and IoT as two contexts where dis-
tributed data aggregation is particularly meaningful, in order, e.g., to save en-
ergy and bandwidth for data transmission to central systems. The survey points
out pros and cons of different approaches, such as *hierarchical* (low communica-
tion overhead, but unreliable), and *gossip-based* (more robustness at the expense
145 of more overhead). Also accuracy is considered, associated with approximated
methods. In section 5.3 we will describe some of the methods available in AP
for performing distributed data aggregation; despite the fact that the commu-
nication model of AP is gossip-based, also hierarchical methods can be easily
implemented.

150 An interesting proposal for improving the efficiency of data retrieval is [14],
where a ML module acts as a sort of “intelligent cache” of the replies to the most
common data analysis queries. A drift-detection mechanism ensures that the

system adapts to changes in the frequencies of the queries posed by the analysts. This can be viewed as complementary to the adoption of AP we propose in this paper, because it optimizes the query processing at the highest layer of the architecture, while AP aims at exploiting the edge devices for improving Data Management performance.

In [15], the authors consider Big Data processing with MapReduce, and propose to exploit limited forms of global coordination among map tasks, in order to significantly improve the efficiency of processing certain kinds of queries (note that the *independence* of map tasks is, instead, one of the pillars of classic Map Reduce). In particular, the SAMs (Situation Aware Mappers) introduced in the paper, can get an aggregate view of the job execution state by accessing the ZooKeeper DMDS (Distributed Meta-Data Store), thus making globally coordinated optimization decisions. A high-level language for expressing MapReduce queries named Jaql is exploited for issuing queries that, at the low level, are efficiently executed thanks to the extra abilities of SAMs. The typical architecture of an HPC system executing MapReduce is quite different from that of an IIoT, with its layers starting from the edge devices; however, the proposal is interesting because it suggests the importance of researching ways to map (at least partially) data analysis queries typically issued at the cloud layer of the IIoT to efficient AP processes at the edge layer.

In [16], the authors review the role of Big Data Analytics (BDA) in the IIoT setting. They recall that BDA involves several sub-tasks, such as data engineering, preparation, and analytics; and, in addition, the management and automation of the data pipeline. They propose an architectural model called *Concentric Computing*, whereby the elements of a BDA/IIoT system are placed in concentric circles from the external far edge devices, to the outer and inner edge servers, to the cloud services.

According to Concentric Computing, computational and storage resources must be offered by different devices and systems across the complete set of circles. The objectives are expressed in terms of storage, in-network data movement, energy consumption, privacy, security and real-time knowledge availabil-

ity. Therefore, in many cases priority should be given to devices and systems
185 near data sources to ensure real-time or near real-time intelligence near end
points, IoT devices and other data sources in IIoT systems

In [17] the authors propose a Data Management Layer (DML) for the IIoT
that is separated from the Network Routing. They focus on the lower (*Far
Edge*) layer of the IIoT architecture, and consider a typical scenario where a
190 set of source nodes produce data, a set of destination nodes require those data,
and a maximum latency L_{max} is tolerated by destinations. They borrow the
idea of *proxy* from other data distribution contexts (e.g., Content Distribution
Networks [18] and Multimedia Streaming [19]), and dynamically compute a
caching scheme on proxy nodes that aims at improving latency while keeping
195 the number of proxies (and, thus, the data redundancy costs) as low as possible.

In [20], the authors explicitly consider user User Equipment (UE) that fea-
tures 5G connectivity as a means to fill the gap between the intelligence embed-
ded in the tools, shop-floors, and conveyor belts and the cloud services able to
process such information. The main problem becomes that of associating each
200 IoT device to a UE in a (approximately) optimal way. The authors find that
the greedy association scheme, whereby the IoT devices associate with the UEs
with probabilities that are proportional to the number of devices that the UEs
can support, performs best. An interesting aspect of this study is the variation
of several parameters during (simulated) tests, including the number of IoT de-
205 vices, the number of UEs, the data arrival probability at the IoT devices, and
the evolution of uplink data processes of the UEs.

2.3. Programming Ensembles of Devices Spread over Space at the Far Edge

Different development approaches for systems involving a potentially vast
number of heterogeneous devices that need to coordinate to perform collective
210 tasks by relying on proximity-based interactions (as in wireless sensor networks)
have been proposed in literature. In the following we classify them into five
categories, identified by a survey [21].

- 215
 • *Foundational approaches* propose compact formalizations aimed at modelling the interaction of groups in complex environments. Most of them extend π -calculus [22]. They include, for instance: models of environment structure (from "ambients" to 3D abstractions) [23, 24, 25]; shared-space abstractions allowing multiple processes to interact in a decoupled way [26, 27]; and attribute-based models featuring declarative specification of the target of communication for dynamically creating ensembles [28].
- 220
 • *Device abstraction languages* are aimed at allowing programmers to focus on cooperation and adaptation, by making the details of device interactions implicit. They include, for instance: TOTA [29], which supports programming tuples with reaction and diffusion rules; the SAPERE approach [30], which supports similar rules embedded in space and apply semantically; the $\sigma\tau$ -Linda model [31], which supports manipulation of tuples over space and time; MPI [32], which allows to declaratively express topologies of processes in supercomputing applications; NetLogo [33], which provides abstract means to interact with neighbours according to the cellular automata style; and Hood [34], which features
 225
 implicit sharing of values with neighbours.
 230
- *Pattern languages* provide adaptive means for composing geometric and/or topological constructions, with little focus on computational capability. They include, for instance: the Origami Shape Language [35], which allows to imperatively specify geometric folds that are compiled into processes identifying regions of space; the Growing Point Language [36], which
 235
 allows to describe topologies in terms of a "botanical" metaphor with growing points and tropisms; ASCAPE [37], which supports agent communication by means of topological abstractions and a rule language; and a catalogue of self-organisation patterns [38], which organises a variety
 240
 of mechanisms from low-level primitives to complex self-organization patterns.
- *Information movement languages* are the complement of pattern languages.

They provide support summarising information obtained from across space-time regions of the environment and streaming these summaries to other regions, however, they provide little control over the patterning of that computation. They include, for instance: TinyDB [39], which views a wireless sensor network as a database; Regiment [40], which uses a functional language to be compiled into protocols of device-to-device interaction; and KQML [41], an agent communication language.

- *Spatial computing languages* provide flexible mechanisms and abstractions for spatial aspects of computation. They avoid the limiting constraints of the other categories. They include, for instance: the Lisp-like functional language and simulator Proto [42], for programming wireless sensor networks with the notion of computational fields; and the rule-based language MGS [43], for computation of and on top of topological complexes.

As pointed out in [4], the successes and failures of the above languages, suggest that arranging adaptive mechanisms to be implicit helps to ensure simple and transparent composition of aggregate-level modules and subsystems. This observation is further pursued by a recent survey [44], which overviews AP and its foundation provided by the FC.

3. Aggregate Programming in FCPP

AP [4, 44] is an approach for programming networks of devices by abstracting away from individual devices behaviour and focusing on the global, aggregate behaviour of the collection of all devices. It assumes only local communication between neighbour devices, and it is robust with respect to devices joining/leaving the network, or failing (open dynamic topology). Beside communicating with neighbours, the devices are capable to perform asynchronous computations. In particular, every device performs periodically the same sequence of operations, with an usually steady rate:

1. collection of received messages,

aggregate function declaration	
$F ::= \text{FUN } t \text{ d}(\text{ARGS}, t \text{ x}^*) \{ \text{CODE return } e; \}$	
<hr/>	
aggregate expression	
$e ::= x \mid \ell \mid t\{e^*\} \mid ue \mid e \circ e \mid p(e^*) \mid \text{node.c}(e^*) \mid f(\text{CALL}, e^*)$ $\mid t \text{ x} = e; e \mid [\&](t \text{ x}^*) \rightarrow t \{ \text{return } e; \} \mid e ? e : e$	
<hr/>	
type	aggregate function
$t ::= T \mid bt \mid tt\langle t^*, \ell^* \rangle$	$f ::= b \mid d$
<hr/>	
built-in aggregate functions	
$b ::= \text{old} \mid \text{nbr} \mid \text{spawn} \mid \text{self} \mid \text{mod_self} \mid \text{map_hood} \mid \text{fold_hood} \mid \text{mux}$	

Figure 3: Syntax of FCPP aggregate functions.

2. computation of a program that is the same for all the devices, and
3. transmission of messages.

AP is formally backed by FC [5], a small functional language for expressing aggregate programs, which currently has three incarnations as a full-fledged DSL: the Scala internal DSL/library *ScaFi* (*Scala Fields*) [45], the Java external DSL *Protelis* [46], and the C++ internal DSL/library *FCPP* [3]. In this paper we focus on the FCPP incarnation, because it is the only one that lends itself to be ported to devices with constrained resources, such as the ones we consider for IIoT (see Section 4).

FCPP is based on an extensible software architecture, at the core of which are *components*, that define abstractions for single devices (*node*) and overall network orchestration (*net*), the latter one being crucial in simulations and cloud-oriented applications. In an FCPP application, the two types *node* and *net* are obtained by combining a chosen sequence of components, providing the needed functionalities in a mixin-like fashion.

Compared to the original presentation of FCPP [3], we have added a fun-

damental construct for supporting *aggregate processes* [47], namely the built-in *spawn* function (see below). Aggregate processes can be figured as *computational bubbles* that involve a subset of the devices running a given FCPP program; such bubbles can spring out, expand, perform some work, stretch and vanish. Given
290 a computational bubble, a device can be either within the bubble (i.e., participating in the computation and bubble spreading), external to the bubble (i.e., not participating in the computation), or at the border of the bubble (i.e., participating in the computation but not in bubble spreading).

295 A fundamental aspect is that every process instance is automatically propagated by all the participating (internal) devices to their neighbours. Therefore, when a device generates a process, it just needs not to leave it immediately in order to propagate it to its neighbours; and so on. Unless nodes explicitly indicate that they are willing to leave the process, the process will tend to expand
300 to every reachable node. On the other hand, when a device leaves a process, even if it happens to be the process creator, it is up to the other nodes still in the process to decide whether they also want to leave (eventually leading up to the termination of the whole process) or not. It is also possible, however, to explicitly initiate a propagating shutdown of the process (through a special
305 status, see below).

The syntax of aggregate functions in FCPP is given in Fig. 3. It should be noted that, since FCPP is a C++ library providing an internal DSL, *an FCPP program is a C++ program* (so all the features of C++ are available). We use * to indicate an element that may be repeated multiple times (possibly zero).

310 An *aggregate function declaration* consists of keyword `FUN`, followed by the return type t and the function name d , followed by a parenthesized sequence of comma-separated arguments $t\ x$ (preended by the keyword `ARGS`), followed by an *aggregate expression* e (within brackets and keywords `CODE return`). *Aggregate expressions* can be either:

- 315 • a *variable* identifier x , or a C++ *literal value* ℓ (e.g. an integer or floating-point number);

- an *object* of type t built through a class constructor call $t\{e^*\}$ with arguments e ;
- an *unary operator* u (e.g. $-$, \sim , $!$, etc.) applied to e , or a *binary operator* $e \circ e$ (e.g. $+$, $*$, etc.);
- a *pure function call* $p(e^*)$, where p is a basic C++ function which does not depend on node information nor message exchanges
- a *component function call* $\text{node.c}(e^*)$, where c is a function provided by some component, depending on node information but not on messages;
- an *aggregate function call* $f(\text{CALL}, e^*)$, where f can be either a defined aggregate function name d or an aggregate built-in function b (see below);
- a *let-style statement* $t \ x = e_1; e_2$, declaring a variable x of type t with value e_1 referable in e_2 ;
- a *conditional branching* expression $e_{\text{guard}} ? e_{\top} : e_{\perp}$, such that e_{\top} is evaluated and returned if e_{guard} evaluates to **true**, while e_{\perp} is evaluated and returned if e_{guard} evaluates to **false**.

The **old** and **nbr** built-in functions, constitute the fundamental constructs of Field Calculus; in FCPP, they are overloaded to several different signatures:

- $\text{old}(\text{CALL}, v_0, v)$ with v_0, v of type t returns the value fed as second argument v in the *previous round* of computation (thus introducing one round of delay), defaulting to v_0 if no such value is available;
- $\text{old}(\text{CALL}, v)$ is a shorthand for $\text{old}(\text{CALL}, v, v)$;
- $\text{old}(\text{CALL}, v_0, f)$ computes the result of applying f to the value of the whole **old** function at the previous computation cycle (using v_0 if no such value is available);
- $\text{nbr}(\text{CALL}, v_0, v)$ with v_0, v of type t returns the *neighbouring field* of values fed as second argument v in the previous round of computation of

neighbour nodes, defaulting to v_0 for the current node if no such value is available for it;

- 345 • `nbr(CALL, v)` is a shorthand for `nbr(CALL, v, v)`;
- `nbr(CALL, v0, f)` (whose logic is described in [48] as the *share* operator), computes the result of applying f to the neighbouring field of values of the whole `nbr` function at the previous computation cycle of neighbour nodes (using v_0 for the current node if no such value is available).

The newly implemented `spawn` built-in function has the following signature:

$$\text{spawn}(\text{CALL}, p, ks, v_0, \dots)$$

350 and spawns an *aggregate process* corresponding to function p for every *key* in the container ks , passing the *values* of the (possibly empty) sequence v_0, \dots as further input to each of them. The aggregate process function p takes as arguments a key and a sequence of values, and returns a pair consisting of a result and a process status. Currently, FCPP supports overloads of `spawn` for
355 two different types of process status:

1. `status`, that is one of the following constants:

- (a) `terminated`: the node wants to shutdown the computation (propagating to its neighbours);
- (b) `external`: the node is not part of the computation;
- 360 (c) `border`: the node is at the border of the computation (see above);
- (d) `internal`: the node is within the computational bubble;
- (e) `*_output` (where $*$ is one of `terminated`, `external`, `border`, or `internal`): the node is in status $*$ and the output of function p should be returned by `spawn`.

365 2. `bool`, with `true` and `false` corresponding to the `internal_output` and `border_output` values of type `status`.

The `spawn` function itself returns an unordered map from the keys of the processes with an `*_output` state to their output values, so that such output values can be used for further computations in the current round.

370 The other built-in aggregate functions currently available are:

- `self(CALL, ϕ)`, which given a value ϕ of `field<t>` type returns the value $\phi(i)$ taken by the neighbouring field ϕ for the current node (of identifier $i = \text{node.uid}$);
- `mod_self(CALL, ϕ, v)`, which given a value ϕ of `field<t>` type, returns the
375 same value with $\phi(i)$ changed to v , where $i = \text{node.uid}$;
- `map_hood(CALL, f, v^*)` which applies f point-wise to a sequence of local or field values v^* ;
- `fold_hood(CALL, f, ϕ)` which *folds* the values in the range of ϕ of `field<t>` type through the commutative and associative binary operator f of type $(t, t) \rightarrow t$, reducing them to a single value of type t ;²
380
- `fold_hood(CALL, f, ϕ, v)` which folds ϕ as above, using v instead of the value of ϕ for the current device: in other words, it is equivalent to `fold_hood(CALL, $f, \text{mod_self(CALL, } \phi, v)$)`;
- `mux(CALL, e_c, e_t, e_f)`, which evaluates all the expressions e_c, e_t, e_f and re-
385 turns the value of either e_t or e_f based on the Boolean value of e_c ; note how `mux` differs from the conditional branching expression described above which evaluates only the branch selected by the condition.

4. Port of FCPP on a DecaWave Board

390 A fundamental step for using FCPP in real-world IIoT scenarios is porting it to a suitable platform, including hardware and operating system. We have chosen the DWM1001C module produced by Decawave, which is currently used by Reply³ to offer solutions to some of its industrial customers.

²In Field Calculus, a neighbouring field always has at least a value for the current node; thus, folding is well-defined.

³The company which co-operated to the present study: <https://www.reply.com>.

The hardware module. The DWM1001C module integrates: the Nordic Semiconductor nRF52832 general-purpose system on a chip (SoC); the Decawave
395 DW1000 Ultra Wideband (UWB) transceiver; and the STM LIS2DH12TR 3-axis accelerometer. The nRF52832 SoC offers a 64MHz ARM Cortex-M4 CPU with floating-point unit, a Bluetooth Low Energy (BLE) transceiver with Bluetooth 5 support, a 512 KB flash memory and a 64 KB RAM. Decawave also offers a developer board (DWM1001-DEV) with a battery connector, a charging
400 circuit, eight LEDs, two buttons, a USB connector and a J-Link on board debug probe for debugging and logging.

Communication range and energy consumption. The UWB transceiver allows the module to perform communication over an higher range than the BLE transceiver, and to compute the distance between two modules (*ranging*) with a
405 precision of up to 10 centimeters. In particular, in our experiments we measured a range of communication in open air of around 70 meters with UWB and of around 25 meters with BLE, with a ranging error always under 30 centimeters with UWB. We also measured the energy consumption by the UWB transceiver to be around three times higher than the BLE transceiver. In our experiments
410 we powered the modules with 1000mAh 3.7V batteries. Without using the UWB radio and keeping the BLE radio always listening for advertisement at 0dBm we measured 12 hours and 15 minutes of battery life. Setting the BLE radio power down to -12dBm increased the battery life to more than 50 hours. Turning the UWB radio on 5 times a second for the duration of 16 milliseconds
415 to perform ranging, while keeping the BLE radio always listening for advertisement at -12dBm, reduced the battery life to 6 hours and 24 minutes. Keeping the UWB radio always in listening mode further reduced the battery life to 5 hours and 7 minutes. We tuned those measurements to quantify the effect of the listening patterns over both BLE and UWB. The transmission mode of the
420 radios is mutually exclusive with the listening mode, and has negligible impact on battery life, as we verified through experiments.

Software porting. We based our FCPP porting on the existing work of the D3S Research Group of the University of Trento⁴, which includes a port of the Contiki operating system⁵ on the DWM1001C and a UWB driver with
425 ranging API. Contiki is an open source operating system for microcontrollers in the IoT, providing: high level APIs for cooperatives threads (proto-threads, see [49]); timers; and networking (with protocols for each network stack layer). We upgraded the porting to the newer Contiki NG,⁶ which provides a partial support for the C++ programming language required by FCPP. Moreover, we
430 improved the C++ support by integrating the C++ clock API and standard output with the Decawave hardware. Contiki NG offers a low code footprint of just about 100kB and the possibility to configure memory usage to be as low as 10kB. The access to the UWB and BLE features of DWM1001C is granted, respectively, by: a port of the UWB driver for Contiki developed by the D3S
435 Research Group (see above); and by the Soft Device for BLE offered by the Nordic SDK for the nRF52832 SoC.

In order to connect FCPP with the UWB and BLE drivers, we had to extend it. In particular, the `hardware_connector` component included in the library handles the communications between physical (hardware) nodes. The construc-
440 tor of its `node` class receives an object whose type is the class implementing the communication functions on a specific hardware. For our present purposes, we have created two classes (FCPP drivers), one for UWB and one for BLE. In order to work with the `hardware_connector` component, they just need to expose:

- 445 • a constructor taking a `node` which represents the current device;
- a constructor taking a `node` and a data structure for configuring the driver;
- a `send` method taking a vector of characters to send; and

⁴See <https://github.com/d3s-trento/contiki-uwb>.

⁵See <https://github.com/contiki-os/contiki>.

⁶See <https://github.com/contiki-ng/contiki-ng>.

- a `receive` method that returns a vector of messages from neighbours.

The UWB FCPP driver exploits the native UWB driver to broadcast all communications between devices over the CSMA protocol with the UWB transceiver; it reaches a greater distance of communication compared to BLE at the expense of an higher energy consumption. The UWB configuration allows to send messages of size up to 116 bytes.

The BLE FCPP driver exploits the native BLE driver to broadcast the messages using the Bluetooth 5 extended advertisement. Moreover, it uses the UWB transceiver to perform the ranging between devices for computing their distances. The main goal of the protocol for intermixing BLE communication with ranging is that of keeping the UWB transceiver in sleep mode for as long as possible to reduce energy consumption. More precisely, the main steps are as follows:

- when a node sends a message through the BLE native driver, it adds a prefix with a list of neighbour nodes it wants to invite to do a ranging session at the beginning of the next round;
- the node then prepares to do ranging with the neighbours in the list at the beginning of its next round; and
- when a node receives a message through the BLE native driver, and it appears in the prefix list, it prepares to do ranging with the sender at the beginning of the next round of the sender.

Thanks to the synchronization information exchanged by piggybacking the BLE messages, the nodes can turn on their UWB transceivers just for the time needed for performing the ranging operations. The BLE configuration allows to send messages of over 200 bytes, with the actual size depending on the ranging configuration, i.e., on the maximum size of the prefix devoted to synchronize ranging, which is not available for the regular payload.

As mentioned above, a serious constraint of the DWM1001C module is the quantity of RAM, limited to 64kB. Thanks to the small footprint of Contiki NG

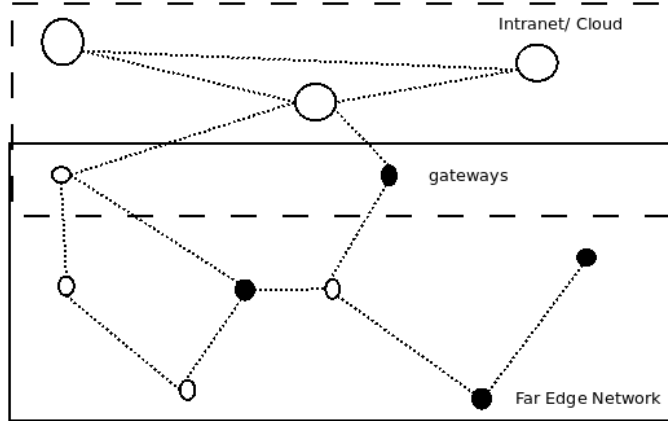


Figure 4: Schema of the Architecture for the IIoT Service Scenarios.

and of FCPP, it has been possible to leave approximately 16kB of stack space and 16kB of heap space to be used by applications built on FCPP.

5. AP Services in an Industrial IoT

480 5.1. Overall Architecture

5.1.1. Hardware Architecture

Figure 4 shows the schematic architecture that we assume for the IIoT scenarios we address. It is derived from the one in Figure 1, but is specifically tailored to the assumptions and focus of this paper.

485 We assume two networks, based on different technologies and covering different layers:

1. a *Far Edge net* \mathcal{N}_{EDGE} composed of low-end computational nodes that communicate point-2-point based on proximity. Corresponds to the *Edge* layer in Figure 1 but assumes specifically point-2-point wireless communication; and
2. an *Intranet and Cloud net* \mathcal{N}_{INET} that connects more powerful systems within the factory among them and, possibly, with external cloud systems, using standard internet technologies and protocols. Corresponds to the

495 *Network* and *Cloud* layers in Figure 1, that we do not need to distinguish for our purposes.

We envision the following types of computational nodes:

1. *fixed* nodes N_F of the \mathcal{N}_{EDGE} net, associated with fixed equipment such as machines, controllers, or fixed sensors (depicted as empty circles in Figure 4);
- 500 2. *mobile* nodes N_M of the \mathcal{N}_{EDGE} net, associated with mobile equipment (e.g., forklifts) and users (depicted as full circles in Figure 4);
3. *gateway* nodes N_G that are nodes that can communicate with both the \mathcal{N}_{EDGE} nodes and the \mathcal{N}_{INET} nodes, thus making it possible to route data between the two nets; and
- 505 4. *cloud* central system nodes N_C that can provide: long term storage; expensive data analysis and ML; connection to a Digital Twin; etc.

It should be noted that the set of nodes N_M can change dynamically quite often, since, e.g., users enter/leave the factory or moving machines are switched on/off. Moreover, gateway nodes $g \in N_G$ may be either fixed or mobile.

510 Sensors and actuators can be associated with both mobile and fixed nodes. For convenience, we spell two important categories:

1. *distance* sensors S_{DIST} , that can detect the distance between nodes of the \mathcal{N}_{EDGE} ; and
- 515 2. *parameter* sensors S_{PARAM} , that measure the values of relevant parameters at their location.

We do not detail how the nodes of \mathcal{N}_{EDGE} communicate with their associated sensors and actuators: they may, e.g., be directly connected through a common physical board, or use a short-range wireless technology such as BLE. We just assume that \mathcal{N}_{EDGE} can retrieve data from associated sensors and issue 520 commands to associated actuators.

5.1.2. Middleware

We do not make specific assumptions about the presence of features offered by middleware software running on the \mathcal{N}_{EDGE} and/or the \mathcal{N}_{INET} nodes. However, a few observations are in order. An AP-based service can be deployed and
525 executed on the architecture depicted in Figure 1 only if:

- heterogeneous nodes in the Far Edge \mathcal{N}_{EDGE} and the gateways N_G can all run FCPP programs (i.e., a porting of FCPP exists for each type of node); and
- the nodes can exchange messages with their neighbours through fixed
530 and/or wireless communication technologies.

Moreover, for applications that exploit the Intranet and Cloud net \mathcal{N}_{INET} , suitable software can be written for communication and coordination with the gateways N_G .

The implementation of AP-based services that run on heterogeneous far edge
535 devices would certainly benefit from the interoperability and code management services offered by a middleware. Similarly, we could benefit from other middleware services spanning the Far Edge, the Intranet and the Cloud layers, such as device discovery and management, security, and privacy. Given the focus of our proposal on far edge nodes, it would be natural to adopt an agent-based or
540 actor-based middleware [50, 51]. In this way, the heterogeneous IIoT devices can be exposed as reusable, distributed actors, which communicate and coordinate with other actors residing at the upper layers of the IIoT architecture.

5.1.3. Services Software Architecture

AP-based services consist of the execution of FCPP programs by the nodes
545 of the \mathcal{N}_{EDGE} . An important role, however, is played by Aggregate Processes and how they are generated, managed, and terminated.

Consider a node n_c (*client*) that must reach another node n_s (*server*) for receiving a service or an information. A simple schema would be to have n_c broadcast its request into the \mathcal{N}_{EDGE} , then collect the replies from the available

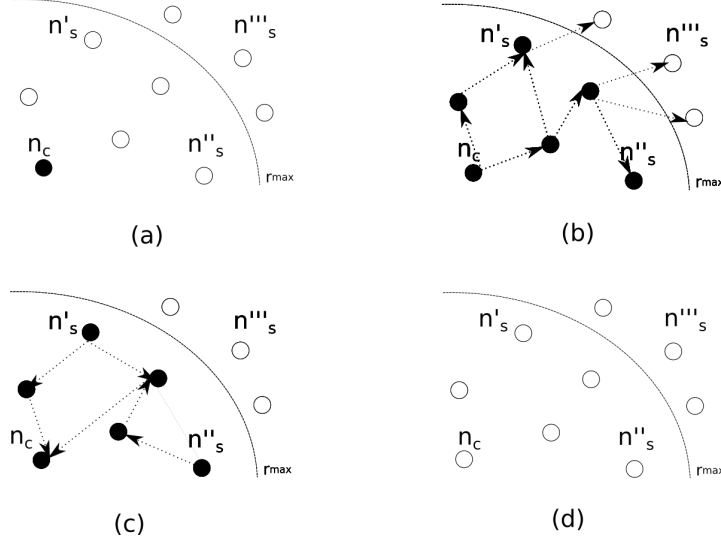


Figure 5: Life of an aggregate process spawned by a client node (a-d). See explanation in the text.

550 service providers n'_s, n''_s, \dots , and finally choosing to adopt, e.g., the reply of the closest one, and discard the others. The problem with this schema, is that, in order for it to work, every node in the \mathcal{N}_{EDGE} should be executing an FCPP program that includes the logic for the broadcast from n_c and the generation and collection of replies from service provider nodes. This is obviously not practical,
 555 since the client can be any node in \mathcal{N}_{EDGE} and there may be many possible types of requests that must be handled and answered according to different logics.

This is where aggregate processes come into play as a fundamental building block of AP systems. In a situation like the one described above:

- The *client* node n_c creates a process, by passing a suitable key (e.g., its node id id_c) to a **spawn** that appears in the FCPP program being executed:

$$\text{spawn}(\text{CALL}, p, \{id_c\}, v_0, \dots)$$

560 Note that, up to the current round the **spawn** has always been executed by node n_c as part of the program, but since it was given an empty set

of keys, it immediately returned as a no-operation (if it didn't execute processes generated by other clients). Figure 5 (a) depicts n_c as a full circle to indicate that it participates to the new process.

- 565 • The function executed by the new process is the one specified as the p argument to `spawn`, and of course depends on how exactly the interaction between n_c and the service provider(s) should happen; it receives the key of the process id_c and the additional parameters v_0, \dots
- 570 • Typically, n_c wants to place a limit r_{max} to the maximum radius of the process expansion, and this can be achieved by passing r_{max} (shown as a dotted arc in Figure 5) as one of the additional parameters v_0, \dots of `spawn` that are forwarded to p .
- 575 • The process created by n_c starts to spread automatically to the neighbours of n_c , and on to more and more nodes $n_p \in \mathcal{N}_{EDGE}$. Figure 5 (b) shows as full circles the nodes within r_{max} to which the process propagates.
- Consider a node n_p to which the process has just been propagated:
 - n_p executes the p function, which, exactly as in n_c , receives the key of the process id_c and the other parameters including r_{max} .
 - The body of function p should be such that node n_p gets to know whether it is beyond the maximum radius r_{max} from node n_c (e.g., by 580 participating to a *gradient* aggregate computation, see section 5.3).
 - If so, n_p should immediately leave the process (i.e., return an `external` or `false` status). In Figure 5 (b), the nodes beyond r_{max} remain empty circles although the nodes within the bubble try to propagate 585 the process to them.
 - Otherwise, it should determine whether it can (try to) provide the service requested by n_c ; if yes, it should send its reply to n_p (e.g., by participating as a producer to a *collection* aggregate computation,

see section 5.3). Figure 5 (c) shows the replies originating from the
590 server nodes n'_s, n''_s flowing towards n_c through the \mathcal{N}_{EDGE} .

- When n_c decides to terminate the process, it initiates the shutdown by returning a `terminated` status, which propagates to the other nodes within the bubble. Figure 5 (d) depicts all the nodes, including n_c , as empty circles to indicate that they have all left the process.

595 5.2. Safety Services

An important set of AP-based services that can be implemented in the architecture of Figure 4 are those that improve the safety of the industrial environment and, in particular, of the people that populate it at any given time.

The typical schema for the AP implementation of a safety service is the
600 following:

1. let N_{SAFE} be the subset of nodes of the \mathcal{N}_{EDGE} net involved in the safety service;
2. nodes N_{SAFE} continuously exchange relevant information (i.e., their velocity) with neighbours, and receive data from their sensors;
- 605 3. in particular, if the node is equipped with a distance sensor $s \in S_{DIST}$, the built-in function `nbr_dist` returns a field of type `field<real_t>` associating each neighbour UID (of type `device_t`) with its distance from the current node (of type `real_t`);
4. the sensor data is evaluated w.r.t. the internal status and with the safety-
610 related data collected from the neighbours;
5. if a danger is detected, the node can react immediately (e.g., stop moving) and initiate an information sharing process to share the detected danger with other \mathcal{N}_{EDGE} and/or \mathcal{N}_{INET} nodes (see sections 5.3, 5.4).

It should be noted that even a simple safety process as the one just described
615 can take advantage of the intelligence provided by AP. For example, the safety threshold of the distance between two nodes can depend on whether the two nodes are not moving, moving towards each other, or moving away from each other. This can be easily achieved with AP.

5.3. Information Sharing for Intelligent Decisions

620 The sharing of information among \mathcal{N}_{EDGE} nodes (without involving the \mathcal{N}_{INET} nodes) can provide many useful, robust and low-latency services. In particular, when executed as an Aggregate Process, it can support the request of a service by a node and the collection of the replies from potential servers, as explained in section 5.1.3.

625 Information sharing can typically follow two alternative ways: the first one assumes that the nodes that directly sense (or, more generally, own) relevant information *spread* it to the rest of the net; the second one assumes that nodes that need information, *collect* it from the other nodes possibly *accumulating* it into a suitable data structure. The spreading and collection of information
630 are fundamental blocks of the AP paradigm, and are sometimes named, respectively, *G*-block and *C*-block in the literature [52]. Referring again to the service request/reply described in section 5.1.3, the client node can spread its request with a *G*-block, and collect the replies with a *C*-block.

The typical schema for the AP implementation of information spreading in
635 our reference setting is the following:

1. let N_{CONS} be the subset of nodes of the \mathcal{N}_{EDGE} net interested in the information produced by a node n_{PROD}
2. node n_{PROD} produces the information and broadcasts it (see below) to all the \mathcal{N}_{EDGE} nodes
- 640 3. the nodes outside N_{CONS} are used just to propagate the information, while the nodes in N_{CONS} also pick-it up and use it for their computations, possibly including making decisions, and posting a reply

Figure 6 shows the implementation of the `broadcast` function in FCPP. First of all, we note that it is a templated function, which parametrizes the types `P`,
645 `T` of the `distance` and `value` arguments: in this case, the `FUN` keyword is substituted with the alternative `GEN(T^*)` listing the parameter types. The `distance` parameter represents the (estimated) distance of the node from the source of the information, i.e. it is 0 for the node that generates the information, and can

```

GEN(P,T) T broadcast(ARGS, P const& distance, T const& value) { CODE
return nbr(CALL, value, [&] (field<T> x) {
return get<1>(min_hood(CALL,
make_tuple(nbr(CALL, distance), x),
make_tuple(distance, value)));
});
}

```

Figure 6: The broadcast function implementation in FCPP.

be estimated with a suitable aggregate function for the other nodes in \mathcal{N}_{EDGE} .
650 The FCPP library offers several functions for the distance estimation, ranging from a basic function `abf_hops` counting the number of hops from the source with the Bellman-Ford algorithm, to sophisticated functions such as `bis_distance` [53], or `flex_distance` [54]. Clearly, a more accurate estimate can be achieved if the underlying system provides S_{DIST} sensors for measuring the distance between
655 each node and its neighbours.

The function body uses the form of `nbr` that takes a lambda function that processes the field `x` of most-recent values exchanged with neighbours to derive the new value for the current node. The lambda applies `min_hood` to pairs (d, v) for each neighbour δ , where d is the distance of δ from the source and v is the
660 value held by δ ; the result of `min_hood` is thus a pair (d', v') corresponding to the neighbour closest to the source. Finally, the use of `get` extracts the value v' , and such a value is returned by `broadcast` and will be associated with the current node in the field `x` when `broadcast` is computed again in the next round.

The AP implementation of information collection and accumulation in our
665 reference setting typically has the following schema:

1. let N_{PROD} be the subset of nodes of the \mathcal{N}_{EDGE} net involved in the production of information that must be collected by a node n_{CONS} ;
2. each node in N_{PROD} produces a piece of information and aggregates it into the data that is collected towards n_{CONS} through the other \mathcal{N}_{EDGE}
670 nodes (see below);

```

GEN(P, T, U, G)
T sp_collection(ARGS, P const& distance, T const& value,
                U const& null, G&& accumulate) { CODE
return nbr(CALL, (T)null, [&](field<T> x){
    device_t parent = get<1>(min_hood(CALL,
                                    make_tuple(nbr(CALL, distance),
                                                nbr_uid(CALL)) ));
    return fold_hood(CALL, accumulate,
                    mux(nbr(CALL, parent) == node.uid, x, (T)null),
                    value);
});
}

```

Figure 7: The single-path collection function implementation in FCPP.

3. when the aggregated data reaches n_{CONS} it is picked-up and used.

Note that, in the second step, it is possible to aggregate the information while it flows from the N_{PROD} nodes to the n_{CONS} . For instance, imagine that a client node n_c has spawned a process to ask for a service, and it then collects
675 the answers of servers n'_s, n''_s, \dots consisting of pairs `pair<real,real>` where the second element is the value of the reply, and the first element is the degree of confidence that the server had in that reply. As the replies flow towards n_c , each node in \mathcal{N}_{EDGE} will propagate only the pair with the highest first element. In this case, the aggregation function is thus the *max* function, but any other
680 aggregation function could be used in the process.

Figure 7 shows the implementation of the `sp_collect` function in FCPP. The FCPP library also offers more sophisticated multi-path collection functions, namely `mp_collect` and `wmp_collect` [55], but the simpler `sp_collect` serves well our current explanation purposes. Moreover, `sp_collect` shows how a tree-based,
685 hierarchical data collection is realized in the AP paradigm. The `sp_collect` templated function has the following type parameters: `P`, of the `distance` parameter, representing the (estimated) distance of the node from the consumer of the information; `T`, of the `value` parameter, representing the aggregate value awaited

by the consumer; `u`, of the `null` parameter, the identity element of the accumua-
 690 tion function; and `g`, of the `accumulate` parameter, representing the accumulation
 function that should take two `T` values and aggregate them into a a single output
`T` value.

Similarly to `broadcast`, the function body uses the form of `nbr` that takes a
 lambda function that processes the field `x` of most-recent values exchanged with
 695 neighbours to derive the new value for the current node. First, the lambda
 applies `get<1>` to the result of a `min_hood` to get the node `uid` of the neighbour
 closest to the consumer; we store the result in a `parent` variable, to stress the
 fact that the flow of information follows a tree⁷ from the furthest nodes to the
 consumer itself.

700 Then, the `accumulate` function is exploited by `fold_hood` to aggregate a field of
`T` values into a single result of type `T`. Such a value is returned by `sp_collection`
 and will be associated with the current node in the field `x` when `sp_collection` is
 computed again in the next round. Using the `max` function, the field aggregated
 by `fold_hood` associates to each neighbour δ' of the current node δ a `T` value as
 705 follows: if δ' has determined that δ is its `parent`, the most recent value sent by
 δ' (contained in the `x` field); otherwise the identity element `null` of `accumulate`.
 In other words, the current device δ aggregates all and only the values received
 from neighbours that chose it as their parent.

5.4. Interaction with the Cloud

710 The sharing of information between the \mathcal{N}_{EDGE} nodes and the \mathcal{N}_{INET} nodes,
 and especially between the edge and the N_C nodes of the \mathcal{N}_{INET} that host cloud
 services, is different than the \mathcal{N}_{EDGE} -level sharing described in the previous
 section in the following main respects:

- all the communications must necessarily go through the gateway nodes

715 N_G ;

⁷It is easy to see that such a tree is a Single Source Shortest Path (SSSP) tree with the
 consumer as source, on the (unweighted) network graph.

- the amount of data collected by cloud nodes can be much higher, in general, than that required by services provided completely within the \mathcal{N}_{EDGE} ;
- typical benefits of the AP paradigm such as low latency, robustness, and privacy, which apply to the \mathcal{N}_{EDGE} services, may not apply to services that also require information to cross the \mathcal{N}_{INET} .

Given these characteristics, the following additional mechanisms can be suitable:

- distribute the workload among N_G gateway nodes as far as possible;
- ensure some redundancy in the data transmitted to the N_C cloud nodes (for improving both latency and robustness).

In FCPP, the distribution of workload can be easily done by partitioning the nodes in \mathcal{N}_{EDGE} in as many regions as there are gateway nodes in N_G . A design pattern specifically created to achieve these goals in a fully distributed fashion through FC itself is the SCR (Self-Organising Coordination Regions) pattern described in [56]. The pattern supports distributed selection of the leaders, but in case all the N_G nodes are used, the selection becomes trivial. Also the formation of the regions can be trivial in its simplest form, whereby each node decides to belong to the region associated with the the closest N_G node.

As for ensuring redundancy, a natural approach is to extend the SCR pattern in such a way that regions overlap, i.e., each node belongs to two or more regions. Again, the criteria adopted by a node to select the regions to join can have varying degrees of complexity depending on the context. If the N_G nodes can be partitioned a-priori into two or more subgroups or *types*, a simple approach consists of each node joining one region per type.

6. Experimental Validation

6.1. Case Study: Warehouse App

To validate the proposed approach experimentally, we consider a scenario inspired by a use case currently being investigated in Reply of smart warehouse

management. We assume that warehouse workers move around a series of aisles
745 with forklifts moving at a maximum speed of 10 km/h (a standard for forklifts).
Pallets containing goods are arranged in a regular grid along aisles, while some
empty pallets are available in a common loading zone, where every load and
unload operation is performed. We assume that the warehouse is managed with
a high turnover, so that goods are placed as close as possible to the relevant
750 point of operation for them, without a fixed placement based on the good type.
High turnover allows for greater efficiency in principle, but it also suffers from
performance degradation as the warehouse starts to fill up: workers may need
to perform long searches for a required good, or even to find an empty space for
a new pallet. As a byproduct, a digital representation of the warehouse status
755 (e.g., a digital twin) is usually inaccurate or impossible. Furthermore, workers
may occasionally run into each other at aisle joints, damaging goods and slowing
down the warehouse operations.

In order to overcome these issues, we propose a warehouse management app
realising the following services:

- 760 1. *preventing accidental collisions*, by warning workers whenever another
forklift is approaching with a speed greater than a threshold, within a
given safety radius;
2. *providing route information* towards either empty spaces and goods match-
ing a given query, presented to the interested warehouse worker by turning
765 on led lights on neighbouring smart devices;
3. *collecting logs* of relevant events (loading/unloading of goods and collision
warnings) towards central points that are connected to the cloud.

We assume that the app runs on a network of DWM1001C modules, where each
pallet and forklift has an associated module. Pallet modules have lower power
770 (to save battery life), and only present output in the form of small led lights
(for routing). Instead, forklift modules are connected with a simple applica-
tion on the workers' personal smartphone, which allows the worker to provide
some basic input (i.e., logging loading and unloading details, issuing routing

requests), shows her some basic output (i.e., collision warnings and additional
775 route information), and stores locally the collected logs, uploading them on the
cloud as soon as possible.

Service 1 is realised as a simple aggregate process, that is spawned by every
forklift module and extends until reaching the safety radius. In this area, the
distance towards the closest other forklift is gathered: if this distance decreases
780 faster than the threshold, a warning is issued.

Service 2 is also realised through aggregate processes. One process computes
routes towards empty spaces (more precisely, pallets that detect an empty space
around them), others compute routes towards goods satisfying given queries, as
they are issued. Each process expands naturally into the whole network, and is
785 terminated everywhere once the routing request is cancelled.

Service 3 is realised through two simultaneous aggregate collection processes,
to enable redundancy and greatly reducing the chances of information losses.
Forklift modules are used as collection sinks, since they can upload data on the
cloud: based on their unique identifier, half of them are assigned to sink group
790 1 and the other half to sink group 2. The logs produced are collected twice,
towards the closest sink in group 1 and towards the closest sink in group 2. The
collection algorithm used is a custom version of *multi-path collection*, designed
to keep the network load low for the specific log collection task. Firstly, hop-
count distances towards sinks are produced. Then, every device computes its
795 partial log collection, by including every log that appears farther than it from
the sink, but *not* also closer than it from the sink. This second condition ensures
that logs stop being propagated when they are already closer to the sink, greatly
reducing the communication load.

6.2. Simulations

800 Firstly, we simulated the operations of a smart warehouse empowered by
the proposed app through the FCPP simulation framework [3] for aggregate

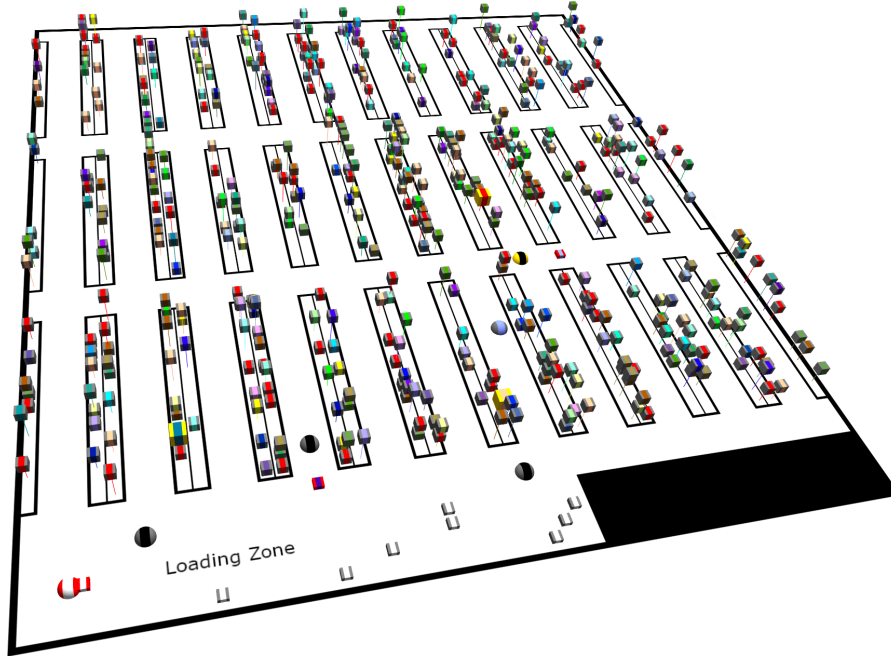


Figure 8: Screenshot of the simulation execution.

computing.⁸ A screenshot of the simulation is shown in Figure 8. The simulated warehouse consists of 22 rows \times 3 columns of aisles; each of them composed by 15 slots in the horizontal direction \times 3 slots in the vertical direction. The bottom part is dedicated to a loading zone (left) and office space (right).
 805

Pallets are represented as cubes with a 1m side (spaced 1.5m from each other), while forklifts are represented as spheres. The content of a pallet is displayed by the colour of its middle band: white represents no content, and various colours are used for 100 different types of goods (randomly generated according to a Zipf distribution [57], so that few goods are very common, and many are uncommon). The middle band of a forklift is coloured analogously according to the good that the forklift is currently searching or loading (if any, black otherwise). For both pallets and forklifts, the lateral bands are grey if
 810

⁸Code available at: <https://github.com/fcpp-experiments/warehouse-case-study>

the device is idling, yellow if it has a led turned on (pallet routing or forklift
815 signalling a collision risk), and red during handling (loading/unloading for fork-
lifts, being carried by a forklift for pallets). Forklifts randomly perform either
a retrieve task of a specific good (picking up a matching pallet, and bringing
it to the loading zone for unload), or a insert task (where an empty pallet is
filled up and then brought to an empty space in the aisles). Tasks are generated
820 randomly during idling times.

In Figure 8, we can see few empty pallets in the loading zone (gray and white
cubes), and several hundreds of loaded pallets in the aisles (coloured cubes in
the grid). In the loading zone, two forklifts are currently idling (gray and black
spheres), while one is currently unloading a pallet (bottom left corner, coloured
825 red and white). A forklift (bottom of the 4th vertical aisle, gray and black
sphere followed by a red and violet cube) has recently loaded a pallet, and is
bringing it to the closest available space. Another forklift (bottom of the 7th
vertical aisle, grey and cerulean sphere) is currently looking for a specific good
(identified by the cerulean colour), following led lights (currently, the yellow
830 and red cube further up in the same aisle). The last forklift (middle-bottom
horizontal corridor, yellow and black sphere followed by a red and cerulean cube)
is bringing back a pallet to the loading zone for unloading. Since these last two
forklift are quickly approaching the same intersection, a collision warning is
triggered (the external yellow bands of the last forklift).

835 Figure 9 presents few performance indicators of the proposed app through
the course of the first 500 seconds of simulated time. The size of messages is
usually below 150 bytes, with peaks below 250 bytes: almost every message is
small enough to be sent, as the message limit of the modules is currently of 222
bytes (and 20 bytes are used by the simulation logics, and would not be used in
840 a deployment). Every log that is created is eventually received, but only about
70% of them are received twice in both sink groups, while another 30% is only
received in one sink group, proving the effectiveness of the redundancy strategy.
Across the simulation, at most 2 logs are created simultaneously (and never
more than one in a single device), while a single sink may collect up to 3 logs in

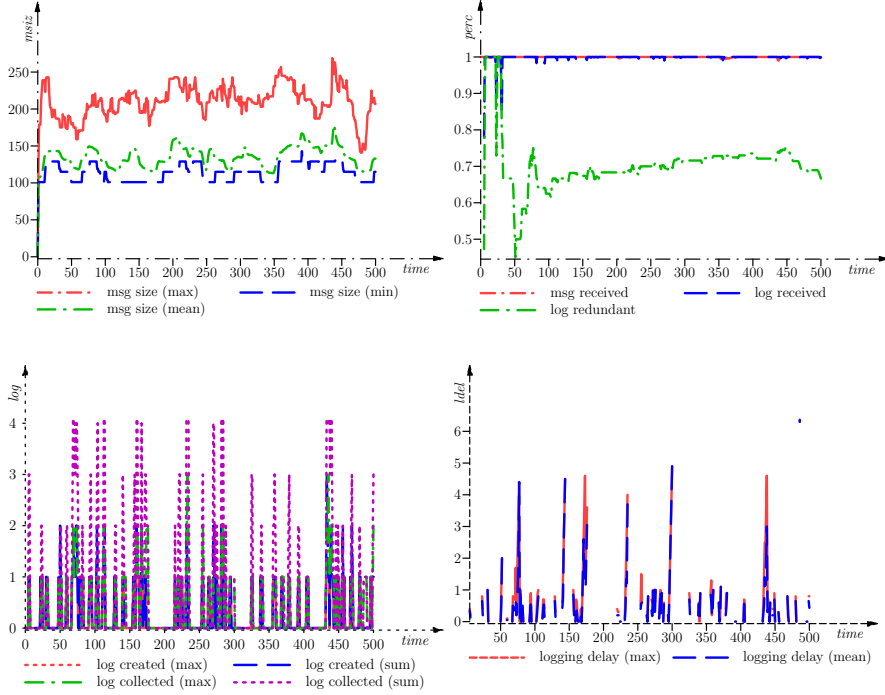


Figure 9: Plots of simulated performance over time: message size in bytes (top-left); percentage of messages delivered, log received at least once and received twice (top-right); logs created and collected (bottom-left), average delay of log collection (bottom-right).

845 a single round (with 4 total logs collected in the same round by sinks overall). The average delay between the log creation and collection is very small, being mostly below 5 seconds (missing parts in the bottom-right graph correspond to times when no log was collected, so that no delay was computable).

6.3. Physical Deployment: a Proof-of-Concept

850 We validated the aggregate program implemented for the simulation on a batch of twenty DWM1001 modules. We used a custom DWM1001 module developed by Reply, which included a buzzer and an additional 32kb flash memory on which we saved the state of the computation at each round in order to resume it in case of device failures (which triggered automatic reboots).

855 The devices were physically deployed in the Reply’s laboratory as visible

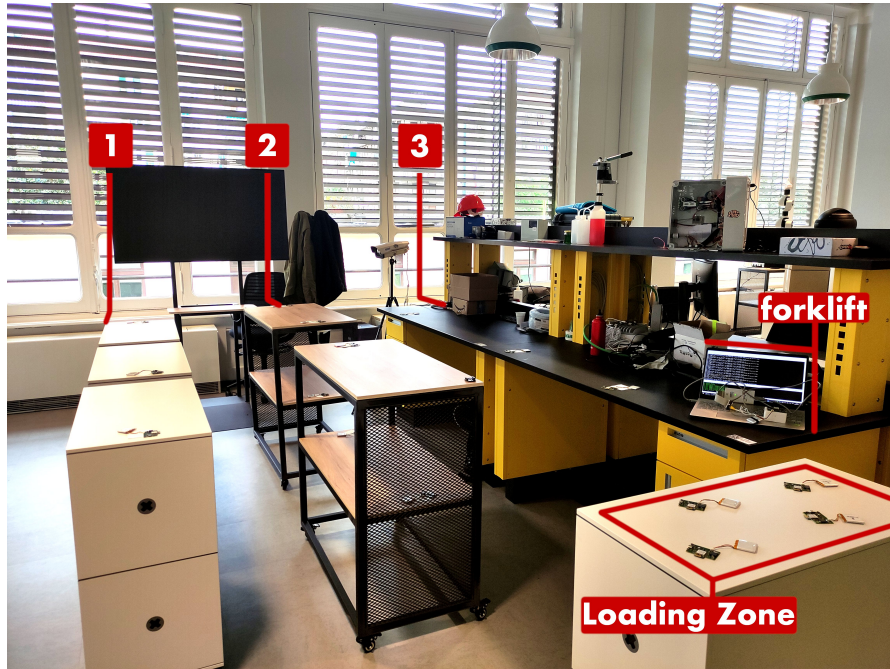


Figure 10: Layout of the devices in the Proof-of-Concept deployment.

in Figure 10. One module was configured as the personal device of a forklift operator, and kept connected to a PC to read the logs in real time (Figure 10 right). Four other modules were configured as being attached to empty pallets in the *loading zone*, realised by a separate cabinet (Figure 10 bottom right). The remaining 15 modules were configured as being attached to pallets having three different kinds of goods already loaded (of different abundance). These modules were arranged in a grid-like configuration with a step of about $1m$ to mimic warehouse aisles, consisting of three parallel rows and three different levels of elevation (Figure 10, aisles numbered from 1 to 3).

We configured FCPP to use the BLE driver broadcasting each message three times at intervals of 10 milliseconds to account for collisions, using a transmission power configured to $-12dBm$ to reduce the range of communication so that not all devices were able to communicate with each module even in the reduced space available for the test. We also ensured that each device could ask for

870 ranging with at most two other devices on each round to limit collisions and
battery usage.

We tested the scenario on which the operator searches for a pallet containing
a random kind of good followed by its unloading near the empty pallets. In the
scenario the operator interacts with the modules by using the button available
875 on them, while receiving feedbacks from patterns of device vibration. The op-
erator starts the request to find a kind of good by pressing the button on the
personal module, then follows the vibration of the loaded pallets until reaching
one containing the requested goods. At this point, the module on that pallet
starts to vibrate intermittently and the operator delivers it back to the start-
880 ing area and marks the pallet as empty by pressing the button on the pallet's
module. This operation was repeated three times without resetting the devices.

At the end of the test the FCPP logs from the personal module of the
operator were collected on the PC to verify that the network presented the
expected behavior. Thanks to the resilience of the AP paradigm, the network
885 was left in a consistent state, with all operations consistently performed, in
spite of a quite high rate of message delivery failure, and devices occasionally
restarting due to memory or other issues.

6.4. Threats to Validity

External Validity. The simulations (in Section 6.2) consider a specific case study
890 (a Warehouse App), which was identified by Reply. Considering different IIoT
scenarios and case studies might result in different values of the performance
indicators shown by the simulations. We plan to consider other IIoT scenarios
and case studies in future work.

The proof-of-concept physical deployment considered a particular pair of
895 device and OS, which was identified by Reply. Considering a different device
and OS might result in a different outcome of the physical experiment. However,
the DWM1001 board and ContikiNG OS provide a very restrictive platform, and
we expect that other platforms would be no more challenging.

Using an higher number of devices configured as forklift wearables may lead

900 to different results. A single wearable was used due to the availability of only one
connector to see the logs in real time from a PC, and because of the hardware
being able to communicate to operators only through vibrations. In this setting,
multiple operators interacting at the same time would not be able to distinguish
the indications relative to them. We plan to repeat the experiment with multiple
905 wearables once we manage to get better feedback from the devices.

The deployment was performed in a reduced scale, due to the availability of
space in Reply’s laboratories. Repeating the experiment on a real warehouse
scale might produce different results, although we expect that tuning the radio
volume should compensate for the difference in scale. We plan to repeat the
910 experiment on a more realistic warehouse model in future work.

Internal Validity. We ran a few randomised computer simulations of the Ware-
house App, and found that the behaviour across the simulations was consistent
and expected. However, no proper statistical analysis of the results across differ-
ent random seeds was performed, and doing this may reveal unexpected issues,
915 although we don’t expect it to happen.

Improving the data structures used by the FCPP modules during the compu-
tation may affect the outcome of the physical experiment, leading to a different
memory consumption and CPU usage. Furthermore, the C++ compiler that we
used for the proof-of-concept physical deployment is deprecated since February
920 2022 with the release of a new compiler. We had to use it because the Nordic
SDK 17.1 bluetooth API is not yet compatible with the new compiler. We ex-
pect that this issue will be overcome with the next release of Nordic SDK, which
we expect to come in July. Using the new C++ compiler in combination with
the new Nordic SDK may affect the outcome of the physical experiment. We
925 plan to repeat the experiment as soon as a new release is available.

7. Conclusions

We have considered intelligent services for the IIoT, deployed on Far Edge
devices placed at fixed locations in the workshop floor, or attached to people

and moving machines; edge gateways allow such services to share information
930 with cloud servers.

Previous work on offloading part of the computational and storage needs to
the Far Edge of the IIoT mostly focusses on data management and proposes
architectural schemes to satisfy specific needs of efficient storage distribution
or edge-to-cloud communication (c.f. Section 2). Compared to such existing
935 work, we show that by exploiting the `spawn` construct of FCPP it is possible
to implement any kind of service that a set of client nodes may require from a
set of potential server nodes. Such services, provided by querying the Far Edge
network, cover diverse areas as safety, information retrieval, and path planning.
Additionally, the AP paradigm guarantees “for free” that the system is open and
940 adaptable, thus allowing node failures, mobile nodes, and nodes joining/leaving
the network at any time.

A valuable contribution of the paper is the actual deployment of AP-based
applications on physical IoT boards with highly constrained resources. Without
the highly optimized FCPP library it would have been impossible to achieve
945 these results. Alternative libraries implementing AP based on the JVM [58],
would introduce a memory footprint that exceeds by far the resources of the
target devices.

We want to further pursue the research described here in several directions.
First of all, we would like to experiment with the physical deployment in a full-
950 size, real world factory setting, to assess the scalability and reliability of our
systems when faced with a noisy, highly dynamic environment. In particular,
we envision the need for a better synchronization between FCPP computation
rounds and the ranging operations, and for retransmission protocols, since with
the current deployment many messages are lost. The deployment of a larger
955 number of devices in an area corresponding to a real warehouse should also
provide valuable feedback for tuning our system.

We would also like to exploit the ranging capabilities offered by the De-
caWave boards to implement an efficient and accurate cooperative RTLS (Real
Time Location System) based on FCPP. Such a service would open the way for

960 many other interesting services to be offered at the Far Edge. In particular, we
envision the possibility of designing “intelligent” triangulation algorithms for
3D position estimation, to be exploited in routing and discovery services.

Finally, we are considering to apply our approach to scenarios involving large
numbers of mobile robotic agents that need to coordinate in an indoor space
965 (e.g., factory, warehouse) to achieve global goals.

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