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Improving devices communication in Industry 4.0 wireless networks☆

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ABSTRACT

Internet of Things (IoT) and cyberphysical system (CPS) technologies play huge roles in the context of Industry 4.0. These technologies introduce cognitive automation to implement the concept of intelligent production, leading to smart products and services. One of the technological challenges related to Industry 4.0 is to provide support to big data cloud based applications which demand QoS-enabled Internet connectivity for information gathering, exchange, and processing. In order to deal with this challenge, in this article, a QoS-aware cloud based solution is proposed by adapting a recently proposed seamless resources sharing architecture to the IoT scenario. The resulting solution aims at improving device to cloud communications considering the coexistence of different wireless networks technologies, particularly in the domain of Industry 4.0. Results are obtained via simulations of three QoS demanding industrial applications. The outcomes of the simulations show that both delay and jitter QoS metrics are kept below their specific thresholds in the context of VoIP applications used for distributed manipulators fine tuning control. In the case of video-based production control, the jitter was controlled to meet the application demands, and even the throughput for best-effort supervisory systems HTTP access is guaranteed.

1. Introduction

Industry 4.0 introduces several changes to the original approach of industrial automation. IoT and CPS technologies play huge roles in this context introducing cognitive automation and consequently implementing the concept of intelligent production, leading to smart products and services (Drath and Horch, 2014). Besides the aforementioned technologies, Industry 4.0 typically relies on big-data cloud based applications which demand QoS-enabled Internet connectivity for information gathering, exchange and processing.

Flexibility and scalability are important requirements of Industry 4.0, since the physical environment of the factories is in constant change. Implementing these requirements demands dealing with the disposition of the sensors and actuator devices in the factories, and how easily they can be displaced, introduced, and reorganized (Freitas et al., 2013). This flexible environment can be attained by diminishing the needs for cabling to connect the devices, which is possible using wireless technologies.

Implementing a QoS-aware cloud based solution is challenging in the context of wireless connections and demands three main issues to be tackled (Wollschlaeger et al., 2017): (I) the coexistence of different wireless protocols and systems, (II) interoperability between communication systems, and (III) seamless engineering to allow adaptive factory operation. In order to deal with these issues, in this article, a recently proposed seamless resources sharing architecture (Kunst et al., 2016a,b; Fernandez et al., 2017) is adapted to the IoT scenario aiming at improving the device to cloud communications considering the coexistence of different wireless networks technologies, particularly in the domain of Industry 4.0.

Simulation scenarios are implemented in Matlab based on an analytical model to consider the coexistence of three different wireless technologies to provide Internet access: 5G, 4G, and IEEE 802.11 base stations. Traffics with various QoS requirements are considered to assess the behavior of the proposed solution. VoIP applications are implemented to evaluate situations where delay and jitter metrics are important; Video transmissions are analyzed to consider jitter dependent applications; and best-effort services are also considered to evaluate how the proposed solution deals with applications with no QoS requirements.

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The remainder of this paper is organized as follows. Background aspects on Industry 4.0 and different approaches of network resources sharing are presented in Section 2. Related works are discussed in Section 3. The design of the network resources sharing architecture is presented in Section 4. Details on the performance evaluation and comparison with related approaches are provided in Section 5. Finally, conclusions and directions for future work are presented in Section 6.

2. Background

2.1. Industry 4.0

Industry 4.0 is a term coined to represent the industrial revolution based on the latest technological advances, also known as the fourth industrial revolution. This concept bring together the notions of CPS (Lee et al., 2015), advanced data communication systems (Wollschlaeger et al., 2017) and embedded intelligence (Wang et al., 2016) . The merging of these technologies also leads to the emergence of related concepts such as Industrial IoT (IIoT) (Civerchia et al., 2017). The architecture of a CPS belonging to an Industry 4.0 scenario is typically organized considering three levels: (I) Physical Objects, (II) Cloud Platform, and (III) Applications and Services, as shown in Fig. 1 (Drath and Horch, 2014).

Industry 4.0 scenarios make possible the interaction of physical and virtual objects. Physical objects are manipulated by means of their virtual representations, which by their turn provide services, that at the end, support applications for highly detailed product customization, precise and timely logistics supply chains, and efficient product delivery. This entire production setup has a representation in the cyberspace, from the smallest and least significant raw material up to the complete product and all the industrial machinery (Rosen et al., 2015). The basis for this emerging industrial environment is the efficient data transmission, supported by wireless communication technologies, in which 5G is a highlight as a key enabling technology. Products can autonomously decide for their best and most optimized way through the production process, exchanging data with other components as well as with the industrial machinery and all the logistics chain.

The physical objects use the mentioned network infrastructure to communicate with the cloud platform. The cloud platform itself provides five basic kinds of services to allow reliable and secure communication among IIoT devices in the context of Industry 4.0 applications: (I) storage, (II) big data processing, (III) topology related definitions, (IV) documentation, and (V) security related issues. The top level provides examples of the classes of services that can be supported, according to five groups: (I) Surveillance, (II) Manufacturing, (III) Transportation and Logistics, (IV) Infrastructure, and (V) Technology (Chen et al., 2017).

2.2. Resources sharing in heterogeneous network scenarios

Network resources can be shared considering different operators and technologies according to three main approaches: (I) Collective Use of Spectrum (CUS), (II) Exclusive Spectrum Access (ESA) and (III) Licensed Shared Access (LSA). These approaches and their ramifications are compiled into a taxonomy show in Fig. 2 and are discussed in the following sections.

2.2.1. Collective use of spectrum

In CUS regime, devices operate under a general authorization, which means that no license is demanded to access network resources. In this regime, a limited amount of network resources, *e.g.* spectrum frequencies, can be accessed by an unlimited amount of independent devices. The access can occur at anytime in a limited geographical area with strict configuration conditions, such as a limited transmission power (Mustonen et al., 2014).

One of the main challenges faced by CUS regime is the unlimited and typically unpredictable amount of devices competing for the available network resources. This situation is obvious for unlicensed technologies, such as those which operate in Industrial, Scientific, and Medical (ISM) frequencies, especially in the 2.4 GHz range of frequencies, since many devices are sharing the access to the frequencies, what may lead to mutual interference. However, even in scenarios where a network operator is providing and consequently controlling resources access, for example, when IEEE 802.22 networks are implemented, it is not guaranteed that the transmissions will be interference-free, what leads to an uncertainty related to the QoS provided to each device.

Recent research has deeply explored CUS, especially correlating it to the concepts of Software Defined Radio (SDR) and Cognitive Radio Networks (CRN). One of the more important works in this area was proposed by Akyildiz et al. (2008). Gardellin et al. (2013) dealt with coexistence of different CRNs composed of a TV transmitter and diverse CRN cells which provided access to microphones as primary user and IEEE 802.22 devices as secondary users. The coexistence problem is stated in terms of channel assignment between the cells considering both a cooperative and a non-cooperative scheme for coexistence.

2.2.2. Exclusive spectrum access

ESA is typically implemented by commercial network operators. With this model, a given operator obtains exclusive access to a certain frequency range. The spectrum access is controlled by regulatory authorities which lease portions of the spectrum for exclusive usage, in concessions that last for long periods (*e.g.* 15 or 30 years). The concession of each frequency range is provided to an unique network operator for the duration of the leasing. Therefore, the exclusive spectrum access provides the licensee with an interference free area of the spectrum.

In the event of resources leasing, the resource renter is demanded to operate in more than one frequency and even in more than one duplexing mode. An example of this kind of implementation can be found in the literature by analyzing the scenario proposed by Palola et al. (2014), which shows the deployment of four base stations simultaneous accessing ESA and LSA bands.

2.2.3. Licensed shared access

LSA is a controlled sharing approach in which a limited amount of devices receive individual licenses to access network resources that are already assigned to one or more incumbent users (Ponomarenko-Timofeev et al., 2016). Incumbent users, in this context, are those network operators which have rights over the network resources. LSA allows resources to be shared during a limited time period in a limited geographical area that is not currently being used by the incumbent. In contrast with CUS, the implementation of LSA considers sharing rules that guarantee a certain level of QoS to all the authorized devices. This guarantee is possible due to the celebration of a Service Level Agreement (SLA) to predefine the access conditions and the amount of resources that will be guaranteed to the LSA user.

SLA can be celebrated to allow various kinds of resources to be shared among different network operators. Based on the definitions of Costa-Perez et al. (2013), these kinds of resources are classified as: Core Networks, Geographically Split Networks, Common Network, Common Spectrum, and Radio Access Network. The authors also proposed physical infrastructure sharing among different wireless service providers. The proposed approach allows on-demand resources negotiation for providing specific services, like VoIP, live streaming, and even the emerging machine-to-machine communication services.

The efforts towards a novel approach for spectrum sharing in the United States are discussed by Sohul et al. (2015). Although the article is a theoretical survey, the authors present and discuss important scenarios of spectrum sharing based on LSA regime. The approach proposed by the authors allows the coexistence of heterogeneous networks, but is not focused on assuring QoS.

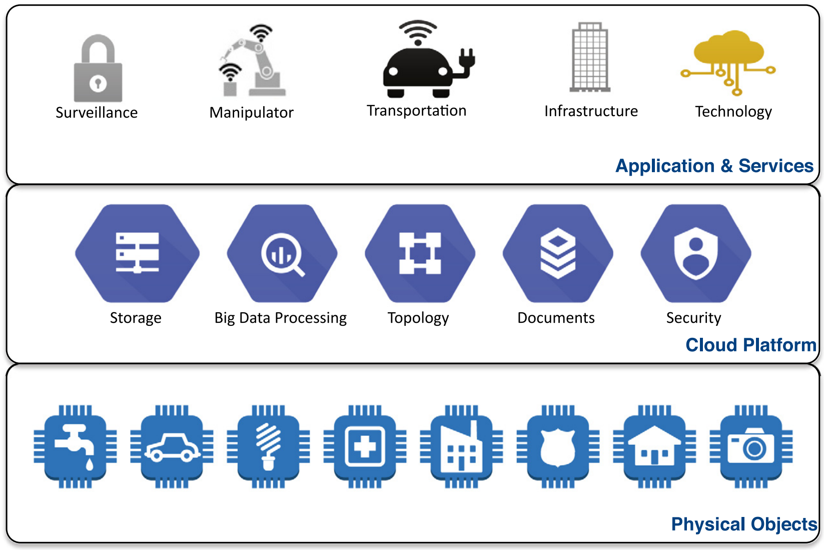


Fig. 1. CPS levels in the context of Industry 4.0.

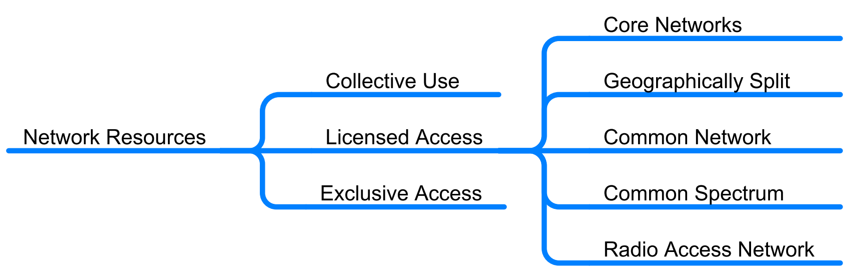


Fig. 2. Resources sharing taxonomy.

3. Related work

In this section, the related works are summarized considering their main features. These features are then compared to the solution proposed in this article. Different approaches have been considered to deal with the devices intercommunication in the context of Industry 4.0. Most of the proposals, however, are concerned in defining the challenges and requirements of implementing high technological solutions which may provide improvements to the existing approach of industrial automation. Although very relevant, these researches are not focused on proposing such solutions or propose solutions which just partially tackle the current research challenges and problems.

In 2005, Ratasuk et al. (2015), published a survey aiming at presenting recent advancements in machine-to-machine communications. Simsek et al. (2016) present the technological basis for the implementation of Tactile Internet using the concepts of 5G systems. The paper highlights the economic impact of the Tactile Internet as well as required changes in the traditional business models implemented by major telecommunication operators. More recently, Wollschlaeger et al. (2017), presented highlights on the expected future of industrial communication. The concepts of IoT and CPS are deeply explored since they are considered trends in automation technology.

Business and technology aspects related to 5G low latency IoT applications are explored by Lema et al. (2017). The authors analyze various 5G use cases that require ultra-low latency. Based on these use cases, the paper shows whether or not such investments are going to be amortized with the implementation of novel business models. High-performance wireless communications for Industry 4.0 are addressed by Pang et al. (2017). The authors claim that critical applications in the Industry 4.0 era demand high performance in terms of reliability and latency.

Table 1
Features of related approaches.

Related work	IIoT	QoS	4G	5G	Ind. 4.0
Ratasuk et al. (2015)			X	X	
Simsek et al. (2016)	X		X		X
Wollschlaeger et al. (2017)	X	X		X	X
Lema et al. (2017)	X			X	X
Pang et al. (2017)	X			X	X
Proposed solution	X	X	X	X	X

The comparison of the proposed solution against related works is based on five predefined features, as summarized in Table 1. The related works are analyzed to evaluate whether or not they deal with (1) scenarios related with IIoT devices coexistence; (2) solutions that consider QoS guarantees to improve the communication among devices which coexist in an industrial automated environment; (3) 4G wireless networks; (4) 5G networks; and (5) Industry 4.0 scenarios.

4. Proposed solution

The architectural design of the proposed solution is presented in Fig. 3. In this case, the traditional CPS architecture is expanded to include two new layers. The first one, called Networking layer, comprises the network access technologies available to implement the communication with the cloud platform. Another additional component is also present in the proposed solution, which is a resources broker, responsible for managing and controlling the network resource allocation, considering both QoS and the cost related to the network access.

In the networking layer, although the proposed solution allows the intercommunication of any network technology, three technologies are

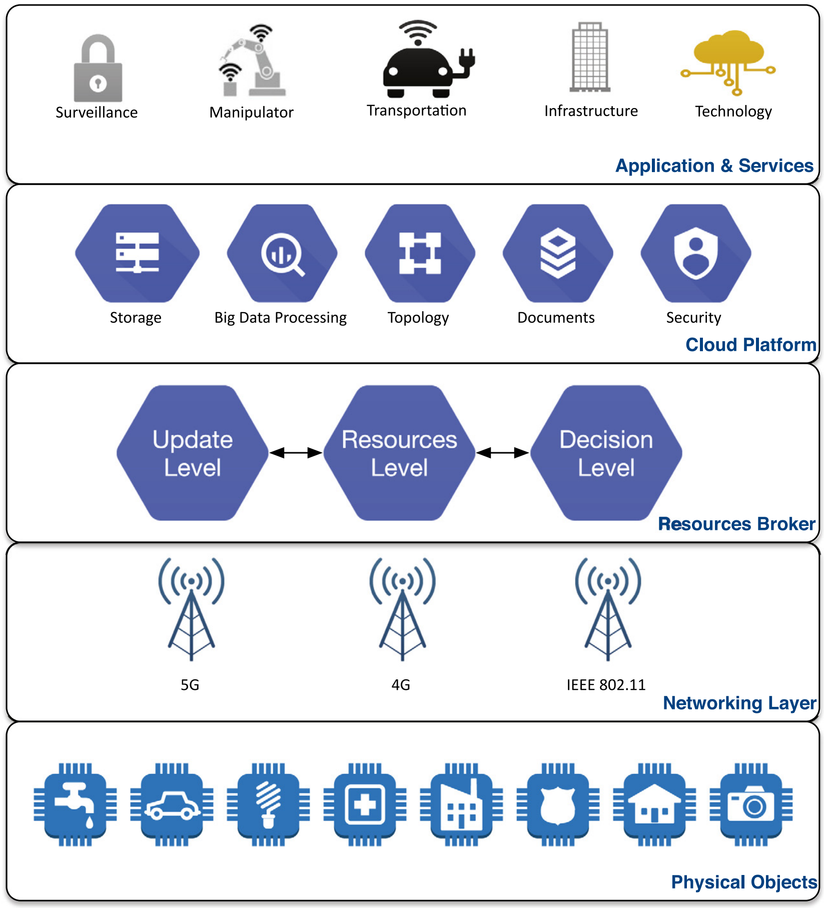


Fig. 3. Architecture design.

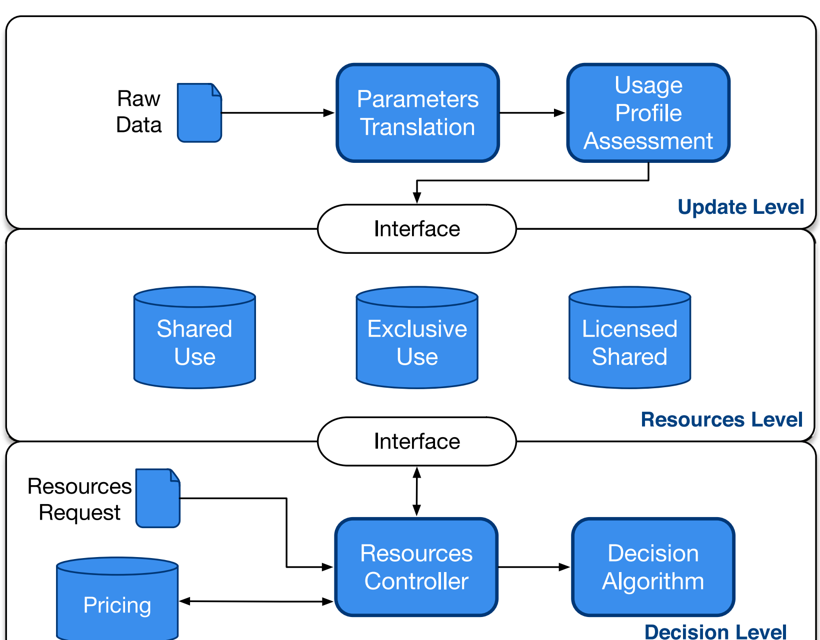


Fig. 4. Resources broker design.

Table 2
Raw update data structure.

Field	Size	Description
Network operator ID	1 byte	Uniquely identifies the network operator in the spectrum sharing architecture
Average delay (expressed in ms)	8 bytes	Updated assessment of the average delay. Performed by the network operator
Average jitter (expressed in ms)	8 bytes	Updated assessment of the average jitter. Performed by the network operator
Average throughput (expressed in Mbps)	8 bytes	Updated assessment of the average throughput. Performed by the network operator

represented, since these are the technologies considered, in this article, for performance evaluation purposes. The decision regarding which network is the best to serve a resource request to access the cloud platform is taken by the resources broker. This component is divided into three levels, named accordingly to the function performed by each one: (I) Update Level, (II) Resources Level, and (III) Decision Level. These levels are interconnected by interfaces which implement the flow of information that allows information exchange among the different levels of the broker. Design details of this component are presented in Fig. 4.

4.1. Update level

The update level is responsible for collecting operation parameters from the network operators which participate in the resources sharing initiative. The updating mechanism is based on the implementation of a polling-based technique, which is controlled by the Parameters Translation block of the broker. After the parameters are translated, a cognitive function is applied to assess the usage profile of each network.

4.1.1. Parameters translation

This block allows the configuration of the interval between polls. The precise definition of such interval is crucial to deal with the trade-off between having accurate information about the current resources usage profile of each network and the overhead generated by the control information transmitted to update the resources broker. Another important function performed by the Parameters Translation block is the translation of the raw update data into a specific format to allow the broker to take proper decisions regarding resources sharing. Therefore, the definition of the structure used by the network operators to update the broker is very important. The definition of this structure is presented in Table 2.

Upon receiving the raw update data structured according to the presented organization, the Parameters Translation block performs a SINR estimation in the radio frequency channel and collects the timestamp of the instant when the raw update information was received. These two parameters complement the ones informed by the network operator and are used respectively to estimate the overall network load and to provide information for historical assessment of the load of each QoS parameter.

4.1.2. Usage profile assessment

The pre-processed raw data is received by the Usage Profile Assessment block, which applies the concepts of cognition to keep track of the historical information provided by the network operators. This historical information is taken into account to define the current usage profile of the network to minimize the effect of abnormal behaviors of the traffic that may occur in realistic operation scenarios. The weight given to the historical information (α) and the weight considered to the most recent update ($1-\alpha$) can be set and modified as parameters of this block. Eq. (1) is applied to calculate the weighted load (ℓ) of each considered QoS parameter of the network operators.

$$\ell = \alpha \cdot \sum_{i=1}^{n} \ell_{(t-i)} + (1-\alpha) \cdot \ell_{(t)} \tag{1}$$

This equation considers a pre-defined number (n) of historical evaluations of ℓ and performs an exponential smoothing to obtain the weighted load of a given QoS parameter (*e.g.* delay, jitter, or throughput). The same equation is applied to the remaining QoS parameters

Table 3
Traffic forecasting errors considering different values of n.

α	% of errors considering $n = 5$			
	HTTP	VoIP	Video	Mean
0	4.8	2.1	6.2	4.36
0.1	4.5	1.7	5.3	3.83
0.3	**4.3**	**1.5**	**5.2**	**3.66**
0.5	4.3	1.6	5.4	3.76
0.7	4.9	2.0	5.7	4.20

Table 4
Traffic forecasting errors considering different values of n.

n	% of errors for $\alpha = 0.3$			
	HTTP	VoIP	Video	Mean
1	4.6	1.8	6.2	4.20
2	4.6	1.8	6.0	4.13
3	4.5	1.6	5.8	3.96
4	4.3	1.7	5.4	3.80
5	**4.3**	**1.5**	**5.2**	**3.66**
6	4.4	1.5	5.3	3.73
7	4.7	1.8	5.8	4.10

to obtain the complete assessment of the usage profile of each network operator. The processed usage profile information is then sent to the Resources Level using the proper interface. The value of α is empirically defined based on a set of simulations. Table 3 summarizes the outcomes of such simulations by relating different values of α with the percentage of traffic forecasting errors considering three classes of service. The value which provided better results was 0.3, meaning that a weight of 0.7 is given to the most updated information and a weight of 0.3 is given to the historical information. The analysis of the mean percentage of errors leads to the conclusion that, in the evaluated scenario, $\alpha = 0.3$ is the value which better fits to minimize traffic forecasting errors. It is important to highlight that the results were also obtained considering other values of n and the behavior of the results was similar. An example of such analysis is presented in Table 3.

The amount of historical evaluations is also considered to calculate the load of a giver parameter (n) is set to 5, based on simulations, which showed that this value provides the best results. The outcomes of the simulations clearly show that, in the considered scenario, $n = 5$ provides the lowest mean percentage of traffic load forecasting errors. Results considering other values of α proved to have similar behavior (see Table 4).

4.2. Resources level

This level of the resources broker is responsible for keeping track of the frequencies allocation plan in order to inform the decision level about the available network resources. In the specific case evaluated in this article, three types of frequencies are considered:

1. **Exclusive Use:** this kind of frequencies relies on licenses granted by regulatory bodies and is controlled by network operators who hold individual usage rights for a specified range of frequencies for a defined period of time in a given geographical area. In such cases, the regulator is responsible for protecting the licensed user against interference and to provide a legal basis ensuring a certain level of QoS. The exclusive use is implemented, for example, in the frequency plan of LTE networks.

Table 5
Resources request structure.

Field	Size	Description
Network operator ID	1 byte	Uniquely identifies the network operator in the spectrum sharing architecture
Class of service (CoS)	3 bits	Identifies the class of service demanded by the resources renter. Used for QoS purposes
Maximum delay (expressed in ms)	8 bytes	The largest delay supported by the application for which the rented resources will be allocated
Maximum jitter (expressed in ms)	8 bytes	The largest jitter supported by the application for which the rented resources will be allocated
Minimum throughput (expressed in Mbps)	8 bytes	The lowest throughput supported by the application for which the rented resources will be allocated
Duration (expressed in hours)	4 bytes	The expected duration of the resources loan
Priority	3 bits	The priority level of the request. The informed value influences on the kind of resources offered by the broker

2. **Shared Use:** refers to the range of spectrum frequencies which are license-exempt. In this case, the right to use the spectrum is afforded to devices that meet certain technical conditions to share the spectrum and which have a low probability of causing interference to other services. The regulator takes no responsibility for protecting individual users of license-exempt devices against interference and does not provide a legal guarantee for ensuring a certain QoS level. An example of license-exempt application is the 2.4 GHz spectrum for the provision of Wi-Fi access service based on the IEEE 802.11 standard.
3. **Exclusive Shared Use:** is the most recent model of spectrum access an is the basis for the so called LSA regime. This kind of frequency range is licensed and works as a complementary source of network resources to MNOs when they face resources shortage. The access to such frequencies is similar to the exclusive use, with the difference that the duration of such access is reduced.

The Resources level of the broker is responsible for providing information regarding the users currently operating in the geographical area as well as about the available ranges of frequencies of each type. Therefore, this level implements three databases which are often updated by the Update level and provide the decision level with information about the current resource allocation status in an on-demand basis. A Exclusive Use database is specified to store regulatory information regarding the exclusive usage rights afforded to license holders. It is important to note that the proposed architecture allows these license holders to share these resources in exchange for profits that may involve financial gains or credit for future resources renting. The Shared Use database allows the resources broker to register opportunistic and license-exempt network operators and users. Such a registration provides important information for the decision level that allow the control of shared resources access. This database does not store information about shared use ranges of frequencies, since the access to these frequencies is by definition not controlled by outside entities, which is the case of the proposed multilevel broker. Finally, a LSA Pool database is defined to store information about ESA frequencies. This database is accessed mainly in situations where primary users are in need of complementing their network resources. The available frequencies in the LSA Pool and the conditions for access are established by the regulatory bodies.

4.3. Decision level

Request for resource allocation aiming at accessing the cloud platform are received and processed by the Decision Level of the multilevel broker. This level is composed of four components: (I) a resources request structure, (II) a resources controller, (III) a pricing database, and (IV) a decision algorithm. Details on each one of these components are provided as follows.

4.3.1. Resource request structure

The Resource Request contains all information demanded by the multilevel broker to decide which resources will be designated for network access, taking into account the QoS requirements and the cost of the resources. A structure is defined to format such requests as shown in Table 5.

Two fields defined in the resources request structure deserve further explanation. The Class of Service (CoS) field is 3 bits long to support the three classes defined in the proposed architecture, plus one bit reserved for future use. These defined classes in the broker architecture are designed to accommodate traffic from different classes of services defined in different network operators technologies. These classes are specified as follows:

- **001 — Real Time Services (RTS):** is the configuration that provides highest level of QoS guarantees. This class is designed for delay and jitter sensitive real time transmissions, for example distributed manipulators fine tuning control and video-based product quality control. In this scenario, the Decision Level of the broker is going to consider all resources providers to decide which one is able to provide the QoS level desired by the resource renter. This kind of selection may lead to higher costs to obtain the shared resources.
- **010 — Multimedia Services (MS):** comprehends non real time multimedia services which typically demand high throughput, but not strict delay and jitter requirements. Since this class is considered a medium QoS service, the Decision Level is going to prioritize cheaper network resources comparing to RTS, such as those provided by the LSA pool of frequencies or even those provided by secondary users, such as IEEE 802.22 network operators or IEEE 802.11 networks available in the geographical area.
- **011 — Best Effort Services (BES):** provides the lowest QoS level in the proposed multilevel broker. BES is designed to support best effort transmissions without strict QoS requirements. Therefore, only free or very cheap shared resources will be considered by the provisioning algorithm. For example, preference will be given to obtain resources from shared use frequency ranges.

The second field of the resources request structure that deserves special attention is Priority. The priority of a request is defined by the resources renter and is related to the amount of investment that such network operator is willing to make in order to rent resources from the resources provider. A high priority indicates that the network operator is able to rent more expensive resources than in a low priority situation. This field was defined to be 3 bits long to allow the setup of three values of priority currently defined in the resources broker, but also to support future enhancements. The currently defined levels of priority are the following:

- **001 — High Priority:** when high priority is set in the resources request structure, the resources controller and the provisioning algorithm searches for resources using all the available network operators and the LSA pool of frequencies. In other words, this means that all the three types of frequencies will be taken into account in the decision process. In this case, the price of the resources will be placed in second plan when deciding which is the best resources renting option for the desired QoS.
- **010 — Medium Priority:** is designed to be used by applications that demand QoS guarantees which are not very strict. In this situation, the decision process will not take into account the more expensive network resources, for example, those belonging to network operators which hold licenses to access exclusive use frequency ranges. Since the price of the resources is taken into

Table 6
Classes of services of the proposed architecture.

Class of service	Supported priorities	Exclusive use frequencies	shared use frequencies	Exclusive shared use frequencies
RTS	High/Medium	X	X	X
MS	All		X	X
BES	Low/Medium		X	

Table 7
Pricing database table structure.

Field	Description
transaction_id	Unique identification of a transaction within the architecture
server_id	Unique identification of the operator which is the resources server
renter_id	Unique identification of the operator which is the resources renter
tickets	Amount of tickets invested in the specific transaction
start_time	Time stamp indicating the expected start of the transaction
duration	Expected duration of the transaction
finish_time	Time stamp indicating the expected end of a transaction

account, the preference will be given to shared use and exclusive shared use frequencies.

- **011 — Low Priority:** focuses on finding cheap resources options for renting. In this case, the QoS level will not be the main concern of the decision process, meaning that the network provider which offers the best cost–benefit considering the trade-off between price and QoS will be selected.

Table 6 summarizes the features of each CoS and the corresponding priorities.

4.3.2. Resources pricing

The resources pricing mechanism is designed to serve as an incentive to commercial network operators to share resources in the context of Industry 4.0 devices intercommunication and cloud platform access. Many proposals on pricing algorithms have been published recently. The majority of such proposals can be classified into three groups:

1. **Pricing:** in this approach, the profit gained by resource provider is specified as a price that must be paid in currency by the resources renter in order to access the shared resources;
2. **Auction:** in this case, many resources providers advertise information about their available resources and the corresponding price. A resource renter then chooses among the available options;
3. **Favors:** this model offers no financial profit to the resources provider. Instead, it is based on favors traded among resources providers which expect to receive similar favors in the future. Generally, the control of such favor exchange is done by implementing the concept of tickets.

The proposed architecture relies on the third group of pricing. Such an assumption is justified because the aim of the proposal is to allow sharing considering networks which will coexist for a long time in the same geographical area. This kind of scenario fits perfectly to the reciprocity demanded by the favors exchange mechanism. Moreover, no payment control is necessary, what simplifies the process of celebrating a dynamic SLA. In practical terms, the Decision Level of the broker implements a Pricing database, which is updated by the Resources Controller when a new resources sharing transaction is completed. This database logs every transactions and keeps track of the amount of resources shared and received by each network operator. The Pricing database implements a table with the structure shown in Table 7 to allow the correlation between two network operators to decide whether a resource request can be served based on the current tickets balance of the operators.

4.3.3. Resources assessment model

The approach defined in this article demands an accurate assessment of the amount of resources controlled by each network operator. The capacity is modeled considering the Shannon's model, based on an adaptation of the solution presented by Siomina and Yuan (2012), as defined in Eq. (2). The channel bandwidth (B) is considered to calculate the theoretical channel capacity (C). P represents the transmission power, g is the gain provided by the transmitting antenna, and σ^2 is the noise power. Besides the SINR, the link efficiency (η) is considered to model a more realistic scenario.

$$C = B \log_2 \left(1 + \frac{P \cdot g}{\sigma^2} \right) * \eta \tag{2}$$

The resources demand in a given instant of time ($d(t)$) takes into account the individual demand ($d_i(t)$) of the ith active connection of each network operator. The total number of active connections is represented by n. Moreover, the overhead, caused by both cyclic prefix insertion (ϑ_{CP}) and pilot subcarriers used for synchronization (ϑ_{PS}) is considered. Therefore, $d(t)$ is calculated as defined in (3).

$$d(t) = \left(\sum_{i=1}^{n} d_i(t) \right) + \vartheta_{CP} + \vartheta_{PS} \tag{3}$$

In order to simplify the decision process implemented by the Decision Level of the broker, the resources occupation factor ($\delta(t)$) in a given instant of time is calculated using Eq. (4). It is important to highlight that this equation correlates the current demand ($d(t)$) with the capacity of a network operator (C). The demand is originally calculated in unit of Mb, while the capacity is obtained in terms of Mbps. Therefore, to guarantee the consistency of $\delta(t)$ factor, the demand must be observed during the period of one second, to transform its unit into Mbps before applying the equation.

$$\delta(t) = \frac{\left(\sum_{i=1}^{n} d_i(t) \right) + \vartheta_{CP} + \vartheta_{PS}}{B \log_2 \left(1 + \frac{P \cdot g}{\sigma^2} \right) * \eta} \tag{4}$$

Situations where δ is close to zero represent that resources are underutilized. On the opposite, a value of δ near to 1 indicates that the resources are compromised, what may lead to resources scarcity. The proposed system model allows to simulate the amount of resources which are available to each network operator.

4.3.4. Resources controller

Every time a resource request is received, it is processed by a Resources Controller. This entity of the broker has direct access to the Pricing database. Through the proper interface, it is also able to retrieve information from the databases in the Resources Level. The aim of the Resources Level is to have updated knowledge about the network resources status and feed the Decision algorithm with candidate resources servers for a given request. Towards this aim, the execution of the Resources Controller follows the specification of algorithm 1.

The inputs of the Resources Controller algorithm is a resource request. Such algorithm interfaces with the Resources Level and therefore is able to access Shared Use, Exclusive Use and Licensed Shared databases. In the first stage, the algorithm classifies the resource request according to the priority informed by the requesting operator considering the CoS (as defined in Table 6). The function called $get\_mno(< Types\ of\ Resource >, < QoS\ Parameters >)$ is responsible for searching the databases of the Resources Level to retrieve candidate resource providers which have enough resources to guarantee QoS. This retrieval of information takes into account the restrictions imposed by QoS parameters specified in the resources request, *i.e.* maximum delay, maximum jitter, and minimum throughput.

As stated in Table 6, requests from an application using RTS class of service typically have high priority which will indicate to the algorithm that it should try to obtain resources from all the available service providers databases. MS requests lead the algorithm to prioritize

Algorithm 1 Resources Controller

Require: r ▷ A struct containing a resource request
Require: get_mno([databases], [QoS Requirements]) ▷ A Procedure that returns operators which match the QoS requirements
$p \leftarrow r.Priority$ ▷ Gets the priority of the request
$d \leftarrow r.Delay$ ▷ Gets the largest delay supported by the application
$j \leftarrow r.Jitter$ ▷ Gets the largest jitter supported by the application
$t \leftarrow r.Throughput$ ▷ Gets the slowest throughput supported by the application
switch p **do** ▷ Tries the standard types of operators, as defined in Table 3.3
  case High
    $mno \leftarrow get\_mno([Exclusive, Shared, LicensedShared], [d, j, t])$
  case Medium
    $mno \leftarrow get\_mno([Shared, LicensedShared], [d, j, t])$
  case Low
    $mno \leftarrow get\_mno([Shared], [d, j, t])$
for all mno **do**
  $cost(i) \leftarrow [mno.Id, mno.Price]$ ▷ Gets the price to be paid
if $cost = \varnothing$ & $p =$ High **then**
  return 0
else if $cost = \varnothing$ & $p =$ Medium **then**
  $mno \leftarrow get\_mno([Exclusive], [d, j, t])$
  for all mno **do**
    $cost(i) \leftarrow [mno.Id, mno.Price]$ ▷ Gets the price to be paid
  if $cost = \varnothing$ **then return** 0
else if $cost = \varnothing$ & $p =$ Low **then**
  $mno \leftarrow get\_mno([Exclusive, Shared], [d, j, t])$
  for all mno **do**
    $cost(i) \leftarrow [mno.Id, mno.Price]$
  if $cost = \varnothing$ **then return** 0
return decision($cost$) ▷ Calls the Decision Algorithm

Table 8
Parameters used to calculate the cost.

ρ		κ	
Type of provider	Value	Priority	Value
Shared use	1	Low	1
Exclusive shared use	2	Medium	2
Exclusive use	3	High	3

borrowing resources from Shared Use Frequencies and Exclusive Shared Use Frequencies. Finally, BES is used for low priority services and, therefore, the algorithm will try to obtain resources only from shared use frequencies in the first attempt. In cases where the first attempt to find resource providers in medium and low priority requests returns no result, the algorithm can expand the selection ranges to consider more expensive service.

After accessing the Resources Level databases, the algorithm calculates the cost of each resource available. The cost (ζ), in the proposed solution, follows the model of favors exchanged among resources providers. The cost of each favor is influenced by three main factors: (I) the type of service provider (ρ), (II) the amount of resources currently compromised by the selected resources provider (ℓ) at a given instant of time, and (III) the priority of the request (κ). ζ is calculated using (5).

$$\zeta = \rho \cdot \kappa \cdot \left(\frac{\ell_{RTS} + \ell_{MS} + \ell_{BES}}{L} \right) \tag{5}$$

In this equation, L represents the total amount of available resources in a given resources provider. The values related to the priorities and types of service providers are summarized in Table 8.

It is important to emphasize that the resources broker estimates the initial cost without considering the duration of the loan, since this information is not accurate at this first stage of analysis. After the transaction if finished, the initial cost is multiplied by the duration of the loan. Since the duration of a sharing transaction is computed in unit of hours by the broker, the final price of the favor, as a consequence, will be computed in a unit of tickets per hour.

The Resources Controller algorithm generates an array of candidate resources providers. Each entry of the array is composed of the unique identification of the service provider and the cost of this transaction. The resulting array is used as the input to the Resources Provisioning algorithm. The aim of the Resources Provisioning algorithm is to take a decision on which resource providers is the best to serve a specific request.

4.3.5. Decision algorithm

The decision algorithm receives, from the resources controller, a list of candidate resource providers which in a first analysis have enough resources to guarantee the QoS demanded by a given resources renter. This list is composed of arrays containing the unique identification of the operator within the proposed architecture and the cost of each transmission. Since the analysis conducted by the resources controller takes into account only the current capacity of each network operator, further analysis is conducted in order to analyze aspects related to the expected traffic load of the candidate resources providers for the estimated duration of the resources rental.

This function of the broker is constantly running with the goal of taking in advance decisions to allow the solution to work in network environments where fast evacuation of frequencies may be required. This kind of evacuation is expected especially in situations where exclusive or exclusive shared use frequencies are being rented. This in advance decision demands this level of the broker to forecast the traffic of the network operators to identify possible evacuation routes.

Such algorithm supports both the usage of traffic models or traces to describe expected behavior of the MNOs. In order to forecast the traffic behavior, a MLRM is implemented using Matlab. This model is based on a traffic measurement Y, which is related to a single predictor X for each observation. Therefore, the conditional mean function can be described as in (6), where α is the intercept and β is the coefficient.

$$\mathrm{E}[Y \mid X] = \alpha + \beta X \tag{6}$$

Considering that multiple predictors (n) are available from the traffic models or from the traces, a MLRM is considered, according to (7).

$$\mathrm{E}[Y \mid X] = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \tag{7}$$

The variability of the ith measurement Y around its mean value is specified in (8).

$$\mathrm{E}[Y \mid X_i] = \alpha + \beta_1 X_{i,1} + \beta_2 X_2 + \cdots + \beta_n X_{n,i} + \epsilon_i \tag{8}$$

In this case, the error assumptions for ϵ_i are that $\mathrm{E}[\epsilon_i] = 0$ and $\mathrm{var}(\epsilon_i) = \sigma^2$. The accuracy of the forecast can be measured by the mean absolute percent error (η), which is given by (9). In this equation, e_t represents the actual network occupation based on network traces or traffic models and y_t is the forecast occupation of the same network in a given instant of time.

$$\eta = \frac{1}{n} \left(\sum_{t=1}^{n} \left| \frac{e_{(t)}}{y_{(t)}} \right| \right) \tag{9}$$

The resulting forecast points compose a continuous traffic function, $f(x)$, which describes the occupied area of each analyzed network. In this context, let $f : D \to R$ be a function defined on a subset D of R and let $I = [a, b]$ be a close interval contained in D. This closed interval represents the start and the end time of the forecast. Finally, let $P = \{[x_0, x_1], [x_1, x_2], \ldots, [x_{n-1}, x_n]\}$ be a partition of I such as $P = \{a = x_0, x_1, \dots, x_n = b\}$. Thus, a Riemann sum ($S$) of f over I with partition P is defined in (10).

$$S = \sum_{i=1}^{n} f(x_i^*)(x_i - x_{i-1}) \tag{10}$$

When the number of points in P increase indefinitely, it is possible to apply (11) to calculate the expected occupied area of each network, which can be related to the occupied network capacity.

$$A_{occupied} = \int_a^b f(x)dx = \lim_{x\to\infty} [s^*(P,f)] \tag{11}$$

This value is normalized considering the total capacity (A_{total}) area of each network operator. Its complement therefore represents the percentage of available resources of a given network. Let $\Theta = \{o_0, o_1, \dots, o_{n-1}, o_n\}$ be a set of network operators. Thus, the free capacity percentage of the network operators is given by (12).

$$\forall o \in \Theta, A_{free}(o) = 1 - \left(\frac{A_{occupied}(o)}{A_{total}(o)}\right) \tag{12}$$

As previously mentioned, three CoS are defined to accommodate different types of traffic regarding to the QoS requirements. Based on the CoS requirements and on the amount of free resources of each operator a resources provisioning algorithm is implemented, as defined in Algorithm 2.

Algorithm 2 Decision Algorithm

Require: Θ ▷ A list of candidate resource providers
Require: r ▷ A resource request
Require: $A_{total}(o)$ ▷ The total amount of resources of each operator $\in \Theta$
Require: $A_{occupied}(o) = \int_a^b f(x)dx = \lim_{x\to\infty}[s^*(P,f)]$ ▷ Occupied resources of each operator $\in \Theta$
1: $selected\_operator = \emptyset$
2: $\Theta = sort(\Theta, cost, asc)$
3: $c \leftarrow r.CoS$; $d \leftarrow r.Delay$; $j \leftarrow r.Jitter$; $t \leftarrow r.Throughput$
4: **switch** c **do**
5: **case** RTS:
6: **for all** $o \in \Theta$ **do**
7: $A_{free}(o) = 1 - \left(\frac{A_{occupied}(o)}{A_{total}(o)}\right)$
8: $delay(o) = get\_resources\_level(o, delay)$
9: $jitter(o) = get\_resources\_level(o, jitter)$
10: **if** $A_{free}(o) \geq t$ & $delay(o) \leq d$ & $jitter(o) \leq j$ **then**
11: **return** o
12: **case** MS:
13: **for all** $o \in \Theta$ **do**
14: $A_{free}(o) = 1 - \left(\frac{A_{occupied}(o)}{A_{total}(o)}\right)$
15: **if** $A_{free}(o) \geq t$ & $delay(o) \leq d$ **then**
16: **return** o
17: **case** else:
18: **for all** $o \in \Theta$ **do**
19: $A_{free}(o) = 1 - \left(\frac{A_{occupied}(o)}{A_{total}(o)}\right)$
20: **if** $A_{free}(o) > max\_operator$ **then**
21: $selected\_operator = o$
22: **return** $selected\_operator$

The Decision Algorithm receives a list of candidate resources providers (Θ) which is generated by the Resources Controller, by executing Algorithm 1. This list is sorted in line 3 of Algorithm 2 to prioritize service providers which are offering low cost resources. Based on this ordered list of candidate resources providers, on the CoS and QoS restrictions extracted from to the parameters received in the resources request, the algorithm is going to search for resources providers which are able to guarantee the QoS demanded by the resources renter.

In order to gather the update occupancy status of the network resources, a function called *get_resources_level* is defined to access the databases in Update Level and retrieve the relevant information. The CoS based analysis is conducted in lines 4–21. The difference of approach for each CoS is related to the kind of QoS parameters that each class of service takes into account, as follows:

Table 9
HTTP traffic parameters.

Component	Distribution	Parameters	PDF
Main page size	Truncated Lognormal	Mean = 10 710 bytes SD = 25 032 bytes Min = 100 bytes Max = 2 Mbytes	$\sigma = 1.37$ $\mu = 8.37$
Embedded object size	Truncated Lognormal	Mean = 7758 bytes SD = 126 168 bytes Min = 50 bytes Max = 2 Mbytes	$\sigma = 2.36$ $\mu = 6.17$
Number of embedded objects	Truncated Pareto	Mean = 5.64 Max = 53	$\sigma = 1.1$ $\mu = 55$
Reading time	Exponential	Mean = 30 s	$\mu = 0.033$
Parsing time	Exponential	Mean = 0.13 s	$\mu = 7.69$

- **RTS:** throughput, delay, and jitter are considered (line 10);
- **MS:** throughput and delay are considered (line 15);
- **BES:** only throughput is considered (line 20).

The logical approach of the algorithm is to select the lowest cost among the candidate service providers which are able to guarantee the QoS requirements of the renter. Details on the software implementation of this proposal are provided in the next section.

5. Performance evaluation

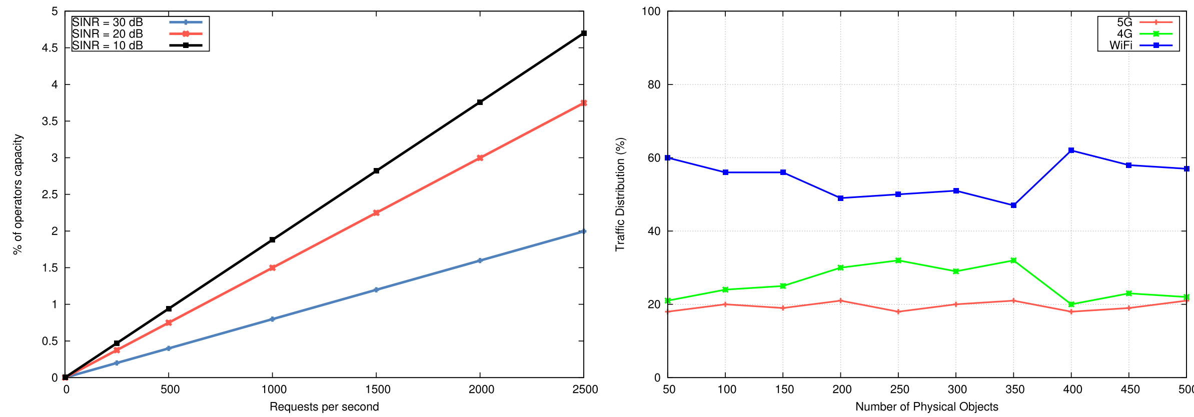
In this section, the performance of the proposed solution is evaluated considering a case study where 5G, 4G, and Wi-Fi network operators coexist in the same geographical area.

5.1. Simulation scenario

To simulate the behavior of the proposed solution it is mandatory to properly model the traffic demands of potential users in the Industry 4.0 context. The traffic model must consider the connection arrival and the amount of traffic demanded per connection. The *System Evaluation Methodology* document, published by the WiMAX Forum (WiMAX Forum, 2008), was selected to model the traffic as it is based on realistic measurements and provides a solid base to estimate the actual traffic demanded by different types of users. The simulations considers three different kinds of traffic: HTTP used for supervisory control and data acquisition (SCADA) systems access (60% of the total traffic), VoIP based manipulators fine tuning control (20%), and video-based production quality control (20%).

The first kind of traffic models best effort HTTP packets. The transmissions are composed of a main page, which has a given number of embedded objects, such as images, scripts, digital twins of industrial elements and other sorts of attached files. After requesting and receiving the files, the browser parses the page to make it readable to the user. The user then reads the page before making a new request. The values of each phase of the HTTP statistical model are presented in Table 9.

VoIP transmissions are modeled according to the parameters of Adaptive Multi Rate (AMR) codec, which presents ON/OFF behavior. The duration of each period is modeled using an exponential distribution with mean of 1026 ms of conversations (ON period) and 1171 ms of silence (OFF period). A Packet Data Unit (PDU) is generated every 20 ms. The third traffic model considers the streaming of video clips encoded with MPEG-4. Each of the videos has variable length, varying from 15 s to 60 s. The display size of the video clip is 176 × 144, what leads to a mean frame size of 2725 Kbytes after the video clip is compressed.



(a) Request Overhead (b) Average Jitter in each MNO

Fig. 5. Overhead and traffic load analysis.

5.2. Performance evaluation

The performance evaluation is conducted based on outcomes of Matlab simulations. The first evaluation is related to the behavior of the system in scenarios in which large amounts of data are transmitted. Results regarding this scenario are presented in Fig. 5. In Fig. 5(a), results regarding the overhead generated by the physical objects to the request network resources to access the cloud platform are presented, showing that even when a very large amount of request messages is exchanged, less then 5% of the operator's resources are compromised for control data transmission. In a realistic situation, the amount of requests per second should lead to an occupation of less then 1% of the network resources. Therefore, analyzing the overhead generated by the proposed architecture, it is possible to conclude that the amount of control information exchanged among the broker and the network operators does not affect the overall performance of the Industry 4.0 network.

In the specific context of IIoT, the resources broker acts to balance the load among the available network technologies, considering both the QoS requirements and the cost of the transmission. In the simulated scenario, the broker aims to improve the amount of resources available for distributed manipulators fine tuning, video-based quality control, and supervisory systems access. Therefore, the traffic load distributed to each network technology is evaluated. Fig. 5(b) illustrates the outcomes of the simulations for this scenario.

The graph considers only the overall IIoT traffic, belonging to all the considered applications and services, without considering the network operators clients traffic, which are not part of the Industry 4.0 scenario. This limited scenario in terms of network operator traffic is considered because the aim is to analyze the capability of the resources broker to properly distribute the traffic demand among the networks, considering the rules imposed by Algorithms 1 and 2, which implement the resources controller and the decision mechanisms, respectively. Therefore, the presence of the original traffic would not allow a precise analysis of the physical objects traffic balancing.

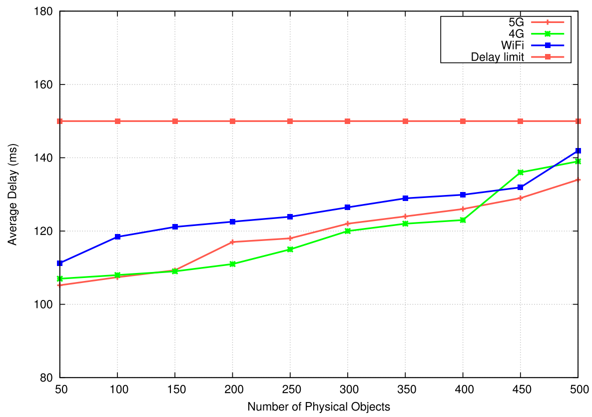
Analyzing the results, it is possible to realize that the majority of the traffic is steered to Wi-Fi networks. This occurs because one of the rules of the resources controller algorithm is to prioritize cheap network resources. Since Wi-Fi networks belong to shared use regime, when Eq. (5) is applied, it leads to a better cost–benefit, considering that the target network is able to guarantee the QoS requirements of the IIoT application. Therefore, an average of 50 to 60% of the traffic generated by the IIoT devices is directed to this network. The remaining traffic is accommodated by more expensive resource providers, *i.e.* 4G and 5G. This occurs because the transmission of manipulators fine tuning and video-based quality control services are classified, respectively, into the RTS and MS classes of service and therefore, these requests are eligible to access more expensive resources when the cheaper resources are not enough to guarantee QoS.

Delay and Jitter are the most important QoS metrics for RTS and MS and therefore deserve special attention in the performance evaluation of the proposed solution. Results regarding these metrics are presented in Fig. 6. The first evaluated metric is the average delay measured in the destination networks. The results regarding the delay are shown in Fig. 6(a), where this metric is analyzed considering a variable number of physical elements and a delay limit to guarantee QoS of 150 ms (Anon, 2016).

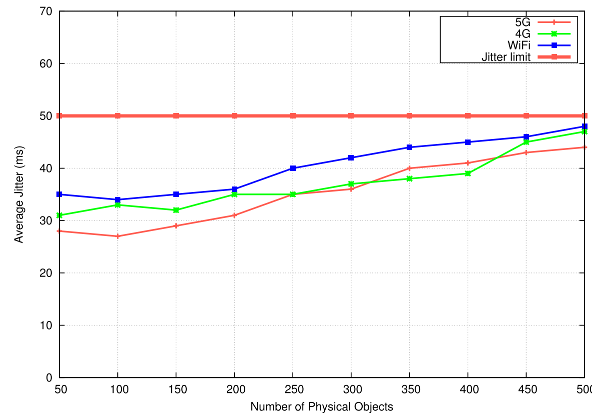
In the worst case observed in the graph, *i.e.* Wi-Fi network operating in a situation where 500 physical objects are accessing the cloud platform simultaneously, the average delay is around 142 ms. Analyzing situations with lower network traffic, it is possible to observe that all network operators are able to guarantee similar delays considering the overall traffic, with values between 100 ms and 140 ms, what is acceptable in terms of QoS. The second important QoS metric for the RTS and MS is the jitter. In this case, the threshold value to guarantee QoS is 50 ms. The results regarding the jitter metric are presented in Fig. 6(b). The jitter values are maintained between 25 ms and 47 ms, leading to the conclusion that the resources broker is able to guarantee QoS considering both delay and jitter metrics.

The results related to delay and jitter metrics are also compared to two state of the art works found in the literature. Both related proposals implement resource allocation algorithms and were originally analyzed by Gardellin et al. (2013). These algorithms are called Random Channel Allocation and Non-cooperative Channel Allocation. Both approaches consider that the shared resource is channel capacity and are applied to IEEE 802.22 networks but are general enough to be adapted to other network scenarios, such as the one analyzed in this article.

The graph presented in Fig. 7(a) compares the average delay. The analysis of the results allows to conclude that until 200 sensors, the performances of all analyzed resources allocation algorithms are similar, due to the low network traffic load. The random algorithm is able to hold the delay under the specified limit in situations in which up to 350 sensors are used, which showed to be the limit of such an algorithm in the evaluated scenario. Comparing the proposed solution with Gardellin's approach, it is possible to observe that, in general, the proposed resources sharing architecture provides a lower value. Moreover, Gardellin's approach is able to guarantee an average delay below the limit when less than 450 sensors are active, while the proposed architecture is able to serve up to 500 sensors. The outcomes of the simulations related to jitter are presented in Fig. 7(b). The proposed solution presents the best behavior, keeping the average Jitter under the specified limit in all analyzed situations.

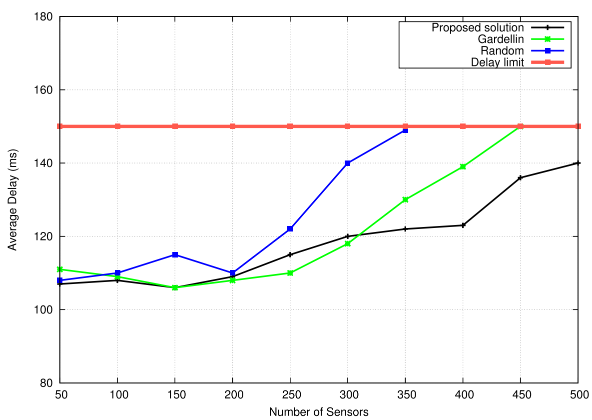


(a) Average Delay in each Network

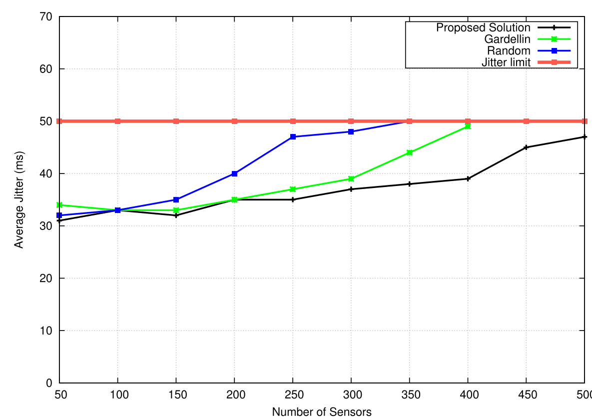


(b) Average Jitter in each MNO

Fig. 6. Delay and Jitter analysis.



(a) Delay metric



(b) Jitter metric

Fig. 7. Comparison with related approaches.

6. Conclusion and future work

This article dealt with the communication of IIoT physical objects with the cloud platform. Three kinks of Industry 4.0 services were considered as scenarios to evaluate the performance of the proposed network resources sharing architecture. VoIP based distributed manipulators fine tuning control was simulated to fit the RTS class of service, video-based production quality control was used to evaluate MS transmissions, and HTTP supervisory systems access was evaluated as a BE service. Results showed that the cost–benefit of resources allocation was taken into account by selecting the lowest cost available network operator which claim to fulfill the QoS requirements. Between 50 and 60% of the traffic generated in this scenario was steered to WiFi networks, which belong to shared use regime and therefore provide cheaper resources. Moreover, both delay and jitter QoS metrics were kept under the specified limit in every implemented service and therefore, QoS was guaranteed.

Future work should conduct an in-depth analysis of the performance of the proposed solution. This analysis could include the execution of the proposed resources sharing architecture in realistic testbeds. A few existing testbeds are compatible with the proposed solution. The most important one is the Cognitive Radio Trial Environment (CORE) from VTT Technical Research Center of Finland, since it is suitable to implement the coexistence of technologies. Moreover, other kinds of provisioning algorithms can be implemented, both via simulation and testbeds, and evaluated to deal with specific network scenarios. Another possible future work is to improve the favor balance between the network operators. Although the solution presented in this article considers the cost of the resources in the decision process, a simple algorithm was implemented without considering the favors balance. Improvements could be focused on the definition of a threshold related to the maximum cost that may be leased before the favor is paid back.

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