Communication Challenges and Solutions between Heterogeneous Industrial IoT Systems

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***Abstract*—Industrial automation systems require communication technologies with high availability, high security and low latency. Accordingly, the current article addresses industrial-specific communication challenges, presenting some of the relevant solutions. In order to prove the usability of the presented technologies with sound results, this paper utilises a primarily Industrial IoT (IIoT) solution, the Arrowhead Framework, to experiment with communication capabilities between different IIoT clouds. The research is limited to three technologies from the LTE UE categories: Cat 3, Cat M1 and NB-IoT.**

The novelty of this paper is that it provides a set of experimental studies on applying different mobile networking technologies to support IIoT applications. The studies are based on our current, real-life measurements.

***Keywords*—Industrial IoT, Industry 4.0, Arrowhead Framework, LTE, Cat 3, Cat M1, NB-IoT, Real-life measurements**

I. INTRODUCTION

Machine Type Communication (MTC) [1] is crucial part of industrial digitisation, where one of the leading and fastest-growing segments is wireless communication. Industrial systems use mostly closed-loop and wired ICT (Information and Communication Technology) solutions, which must be changed to allow remote, efficient and secure communication with other external systems. Thanks to the advancement and evolution of wireless technologies, fast and high-volume data transfer, low-latency, and comprehensive spectrum ranges are widely available over various techniques.

The first goal of this study is to present the essential requirements of industrial communication external to the factory. Industry 4.0 has identified challenges for the data related processes [2], such as data collection across the whole factory, data analysis methods to gather meaningful information and efficient service usage based on the revealed data. Another target here is to show how much data loss the protocols are capable of overcoming with certain background traffic.

In industrial IoT, the special requirements were driving the creation of ”local clouds” [3], within which certain services are available with some guarantees on their QoS (Quality of Service), as well as secure and safe utilisation. There could be, however, need for inter-cloud service exchange between the ”local clouds”, for which other service guarantees should also be provided. This paper investigates some technological challenges of this domain.

The novelty of this paper is to present a measurement composition and methodology, which can simulate cloud-to-cloud communication between the Industrial Internet of Things (IIoT) clouds. Furthermore, the paper aims to verify and validate the behaviour of the examined 3GPP provided protocols through real-life measurements with some generated background traffic, and to show the effect of background noise on data transmission.

The paper is structured as follows: Section II discusses the related work, presenting the identified challenges and the environment of a cellular network with the features of the latest 3GPP standards and some of the relevant works on the field. Section III describes the basics of the used IIoT framework, Arrowhead. In Section IV, the measurement configuration is explained, and the results are examined in Section V.

II. RELATED WORK

Once the different IoT use cases were identified, they created differentiated requirements for connectivity in terms of throughput, latency, security, reliability, amongst others. This leads to enable different approaches and technologies such as Software-defined Networking (SDN) Network Function Virtualization (NFV) and cloud technologies [4].

In this article, the focus is on automation IoT scenarios, more specifically on industrial cloud-to-cloud or inter-cloud communication-related industrial requirements. These are, again, the local clouds [3] defined for industrial IoT, and not to be confused by general-purpose ICT clouds.

A. Inter-cloud communication in industrial environments

The development of ICT has undoubtedly a high impact on the industrial field; moreover, it can be generally stated that the industry needs to meet much higher expectations [5] compared to the general requirements. For the traditional wired industrial networks, the growing number of moving devices, vehicles means further challenges, which exceedingly influence the design and implementation of industrial ICT and MTC. The mentioned factors have all led to wireless networks becoming the optimal choice for most applications and Cyber-Physical Systems (CPS). In order to address the identified challenges [6], i.e. dynamic network access and cross-operator management, a certain level of QoS, security and privacy support and furthermore, billing and charging

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TABLE I
AN EXAMPLE OF INDUSTRIAL NETWORKING USE CASE REQUIREMENTS [11]

Service	**Bandwidth**	**Latency**	**Reliability**	**Packet Error Rate**
Smart meters	few bytes - few kbps	16 ms	99.99%	<6-10
Status information	few bytes - few kbps	16 ms	99.99%	<6-10
Reporting and logging	few bytes - few kbps	1 s	99.99%	<6-10
Data polling	bytes -7 kbps	16 ms	99.99%	<6-10
Control traffic	512 kbps-1 Mbps	16 ms	100.00%	<9-10
Video surveillance	0.5 Mbps-25 Mbps	1 s	99.00%	No specific requirement

functions must be provided. Supporting these, and taking into account the expanding number of IoT devices [7], the most efficient communication solution must be chosen.

Cloud services – either in general, or in the local cloud sense for IoT – must take into account to fulfil essential needs, such as scalability, transparency, performance, security, and even cooperation in heterogeneous environments [8], [9]. In most cases, the continuous transmission of data from smaller sensors is the task, but to stream real-time camera records for an external cloud can also be a use case.

B. Deterministic Networking use cases

For diverse industries that require deterministic flows, methods defined in IETF RFC 8578 [10] can serve as a basis for network scaling. The use cases described by the document differ significantly in their network topologies and specific desired behaviour, providing as a group broad industry context for Deterministic Networking. Regarding the use cases, the RFC identifies the general requirements and further describes possible improvements.

Table I contains an exemplary summary of the possible parameters and the related key metrics for an industrial scenario [11]. The column with the bandwidth examples was taken arbitrarily based on characteristic values.

C. 3GPP Long Term Evolution

The LTE (Long Term Evolution) is a wireless broadband communication standard for mobile devices and data terminals. Over the years, 3GPP has released more standards, and now the LTE specification determines 20 different UE (User Equipment) categories with different attributes, such as download and upload speeds, bandwidth, QoS and transmission latency within the radio access network.

Briefly, an LTE network consists of two main parts: the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC) network. The typical E-UTRAN consists only of evolved NodeBs (eNodeB), which is the connection point between the EUTRAN and EPC and provides radio access to the UEs (in our case, these are the IoT devices) that are within their radio coverage. The EPC allows for UEs, amongst others, the access to the LTE based cellular system, the support of mobility, roaming and different multimedia services. The EPC is further segmented to several functional elements [12] – although detailing these have no relevance from the current measurements' point of view.

There are already studies on the field, that the LTE (Long Term Evolution) based solution can serve the mentioned needs efficiently [13]–[16]. However, the support of these processes would be costly in terms of resource usage if the original LTE standard is considered as the solution. Nonetheless, the LTE allows with low power technologies as well, which can provide high throughput, low power consumption, high spectral efficiency, and improved coverage and cell performance [17]. Using them, a wide range of use cases can be covered. While the LTE standards indicate sound basis, it is not entirely clarified yet how these MTC technologies would operate in real LTE networks due to the imperfect circumstances such as unexpected background traffic, channel failures or other factors which affect or influence the transmission. The following subsection and Table II will describe the proposed and tested LTE protocols provided by 3GPP.

1) LTE Category 3 (Cat 3): The category was introduced in 3GPP Release 8, and it offers via less complexity less network bandwidth and speed. This category can be considered as an intermediate category between LPWA (Low Power Wide Area) and high-speed solutions. However, depending on the field of usage and taking into account the different parameters, there can also be found better solutions in terms of speed or low power consumption. Cat 3 offers a satisfying solution for IoT applications that may require high-quality video streaming or voice service. For Cat 3, Slanina [18] provides with measurement and analysis regarding the throughput and physical layer parameters of Cat 3.

2) LTE Category Machine 1 (Cat-M1): Cat-M1 [19] is a variant of the LTE Category 1, primarily designed for the IoT world. Its main advantage compared to other technologies, is the more efficient battery life. Its download and upload speed are prepared for low to medium data traffic, but it can still provide with the appropriate bandwidth for communication. Here, Cat-M1 offers low-power, battery-friendly solution, and it can support the smallest private networks and bigger industrial systems as well. However, this is currently used for internal communication, but combined with the LTE network; it can also maintain satisfying external communication. Hsieh et al. [20] present a simulation study of Cat-M1 coverage, which can be used for network scaling, using this protocol.

3) LTE Narrowband IoT (LTE NB1, NB-IoT)): 3GPP Release 13 [19] introduced it as an LPWAN (Low Power Wide Area Network) radio technology which provides with a wide range of supports for IoT devices and services. The purpose of NB-IoT is similar to Cat-M1; however, it uses DSSS (Direct Sequence Spread Spectrum) modulation instead of LTE radios. Considering the facts that NB-IoT initially operates out of the Release 8 defined bandwidth range, it can results in higher deployment costs from the operator perspective due to required dedicated frequency allocation. However, due to this technology's capability, in the end, NB-IoT is a cheaper solution because it does not require gateways compared to

TABLE II
PARAMETERS OF THE EXAMINED TECHNOLOGIES

	Cat 3	**Cat-M1**	**NB-IoT**
3GPP Release	Release 8	Release 13	Release 13
Downlink Peak Rate	100 Mbps	1 Mbps	250 kbps
Uplink Peak Rate	50 Mbps	1 Mbps	250 kbps (multi-tone) 20 kbps (single-tone)
Latency	10ms	40ms–400ms	200ms-100s
Bandwidth	1.4-20 MHz	1.4 MHz	180 kHz

other LPWAN technologies such as LoRa [21] and Sigfox [22]. In contrast to Cat-M1, it is more suitable for low data traffic. A clear advantage is that it is even a much more battery and cost-effective solution compared to Cat-M1. Beyene et al. [23] described uplink coverage performance analysis and simulation results, which were verified using by real-life measurements for NB-IoT.

III. ARROWHEAD FRAMEWORK

The Arrowhead Framework [24] is designed to cover interoperability and integration issues for the IIoT world. It supports the collaboration of newly built as well as legacy CPS architectures based on the principles of SOA (Service Oriented Architecture) through applying the SoS (System of Systems) approach. It realises the local cloud concept empowered by inter-cloud communication capabilities.

Each stakeholder has its local cloud(s), working as an SoS. Their systems implement either intra- or inter-cloud information sharing, as well as security- and other policies. The Arrowhead Framework defines three main levels of the systems, as Figure 1 shows. The *Mandatory Core Systems* [25] provide the necessary functionalities. This group includes the Orchestration System (mainly for service discovery and late binding), Service Registry (service providers can announce their active services), and Authorisation System (to provide authorisation, authentication and access). Further, *Supporting Systems* allow general services that are often needed in SoS, so integrators do not have to implement their solutions for such common services. The Arrowhead Framework defines the following systems on this level [26]; the Gateway and Gatekeeper Systems for inter-cloud communication (data and control plane, respectively), the Workflow Choreographer and Executor (to trigger the next step in the process execution), the Event Handler (to circulate status and event information), and the Plant Description System (to keep track of SoS- or Plant-related meta-data), among others. The *Local Cloud Specific Systems* are distinct elements of the SoS; these provide (and in fact, consume) the various application services – in a discoverable, late-bound, loosely coupled way that is defined by the SOA. These are mostly the local systems; from the smallest sensors up to the biggest CPSs.

IV. COMPOSITION AND PARAMETERS OF THE MEASUREMENT

The Arrowhead Framework has standard procedures for connecting different local automation clouds. As in any case, the available protocols must be tested from the framework point of view; it is necessary to check how well it provides services to the layers built on it. This paper presents how the Arrowhead Framework can support secure and reliable data transfer using the relevant standard protocols provided by 3GPP.

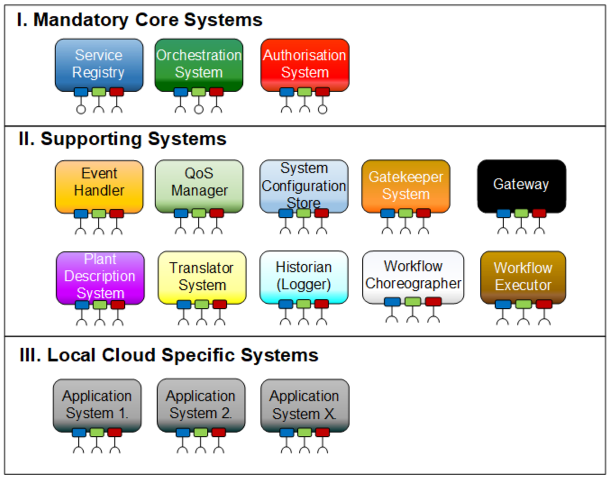

Fig. 1. The core systems of the Arrowhead Framework

A. The measured parameters

To test the technical features of the Arrowhead Framework, we assembled an environment, where the following parameters are measured.

1) Latency: A typical network use case is to transport the periodic data of devices towards one or more gateways. In other cases, the devices shall communicate with each other – in case of the fourth- or the fifth-generation telecommunication networks – via the cellular packet network. The real-time related requirements are one of the keys for these networks.

2) Packet Error Rate (or data loss): As for the communication in many networks, the success ratio of data sending is essential. The high packet loss can raise enormous problems, which has to be fixed by the upper layers. It is natural in a wired network that devices are available most of the times, and probably they do not respond only in case of failures. However, in wireless systems, one of the best features of the terminal equipment is that their receiving circuitry is not continuously switched on, so they wait for a certain time when they will be addressed. For some systems, such as LPWA equipment (e.g., NB-IoT and Cat-M1), this is natural that devices do not respond to the address for minutes.

3) Bandwidth: The available bandwidth between any communication systems is an essential parameter. It is also true that communication systems (in this paper clouds) or in lower layers, the applied communicating protocols shall adapt to the changing environment. In data transportation systems, based on the load, the bandwidth can change on an extensive scale. However, in case of some IoT systems, where the data is minimum, and the traffic is mostly ad-hoc, the available bandwidth for the protocols are not critical at all.

TABLE III
MEASUREMENT ENVIRONMENT VARIABLES

Packet send ratio [ms]	0.25	0.5	5	20	60
Signal strength [dBm]	-115		-100		-60
Background traffic [%]	0		50		100

B. Architecture of the measurement

The measurements were performed under laboratory conditions on a test eNodeB system and a connected EPC. This composition was placed in a test cell isolated from external radio networks where one eNodeB provided the coverage. During the measurements simultaneously, Arrowhead clouds communicate with each other, and the parameters – highlighted in the previous subsection – are measured. To disturb the radio environment, a not Arrowhead specific communication with an External Server is added, as background traffic, which is directly connected to the EPC. For each scenario, 10 000 packages – 200 bytes each – were sent. The role of the Arrowhead framework is the management of the data flow between the internal and external routers; therefore, we placed Arrowhead routers to the edge of the Arrowhead clouds. The architecture of the measurement is shown in Figure 2. The used UEs are Raspberry Pi3 connected to the modems, i.e., Quectel BG-96 device (Cat-M1, NB-IoT) and a Huawei E398 (Cat 3) for the Arrowhead Cloud and Background traffic generation as well. The software regarding background generation was made with iPerf and iPerf3. Furthermore, the validation was built on the External Server by iPerf and Wireshark with an i7 x64 hardware platform. The next subsections and Table III describe the changing parameters during the measurement.

1) Signal Strength: For testing, we have placed the modules in three different signal strengths by mitigating the cell. In the first case, we were looking for a state very close to the base station, where the signal strength was around -60 dBm; therefore the self-measured Cell Signal Quality (CSQ) on the UE was better than 31. In the second case, by applying significant mitigation, the signal strength was reduced to about -100 dBm, where the CSQ was between 6 and 7. Then, in the third case, we were looking for a deep-indoor coverage level where the measured signal strength was about -115 to -123 dBm, where the value of the CSQ varied between 0 and 3. At this level, the device Coverage Extension mode was activated on level 2 for NB-IoT, and the Cat-M1 and Cat 3 devices were unable to connect to the cellular network.

2) Background Traffic: To emulate the real environment, we added another distraction, manually generated background traffic. The volume of background traffic was changed in proportion to the total channel capacity, so the measurement results of the different access technologies remained comparable. The steps were 0, 50, and 100%.

V. DISCUSSION ON MEASUREMENT RESULTS

The measurement results confirm the expected assumptions of the standards, i.e. the higher bandwidth shows higher data rate and less transmission delay. It is also clear from the results that until there was no significant background traffic, PER was close to 0, measured at Open Systems Interconnection model application layer. The peak data rate was always almost as expected based on the datasheets of the modems and vendors. In other cases the packet error rate was nominal. Therefore in this article, we concentrate more on the highly variable delays of different access technologies. The following subsections describe the results, focused only on the main parts, which are summarised by Table IV.

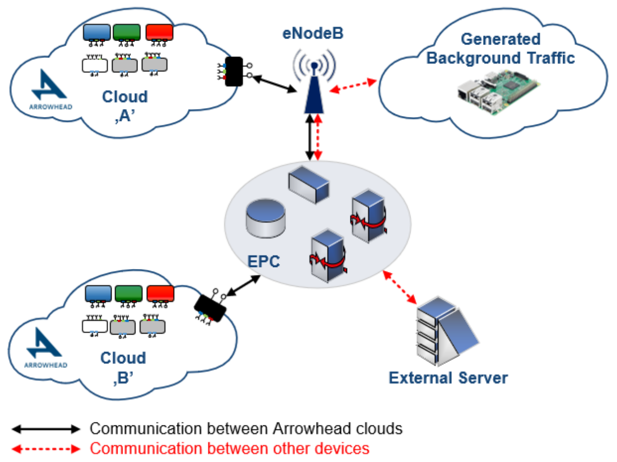

Fig. 2. Architecture of the measurement

TABLE IV
AGGREGATED (MEDIAN) RESULTS OF MEASUREMENTS

	Cat 3	Cat-M1	NB-IoT
Downlink Peak Rate	70 Mbps	312 kbps	23 kbps
Uplink Peak Rate	22 Mbps	52 kbps	20 kbps
Latency	12–549 ms	41–6436 ms	15-38791 ms
Packet Error Rate	0.3%	0.5%	0,13%

A. Evaluation of Cat 3 measurement

Category 3 devices are the most "powerful" devices in this comparison measurement scenario. They occupy the most bandwidth in the air and consume the most electrical energy. As shown in Figure 3, where the signal strength was around -60 dBm, the latency is very low. The minimum value was approximately 12 ms. In the case of higher background traffic, the delay increased significantly. In case of worse coverage where the signal strength was around -100 dBm, the difference is also nominal as shown on Figure 4. It is worth to mention, in case of -115 dBm signal strength the device was unable to connect. As shown in the aggregated results at Table IV, the downlink peak data rate was around 70 Mbps, which show the power of the network. However, in the case of inter-cloud communication, the clients are all cellular devices, so their maximal uplink data rate will be the maximal data throughput to the targeted cloud.

B. Evaluation of Cat-M1 measurement

In case of no background traffic, the packet delay of Cat-M1 devices is similar to Cat 3 as show on Figure 5 and

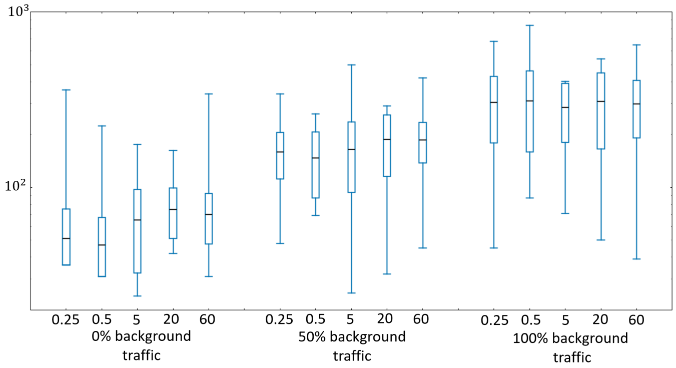

Fig. 3. Packet delays [ms] on Cat 3 traffic, -60 dBm

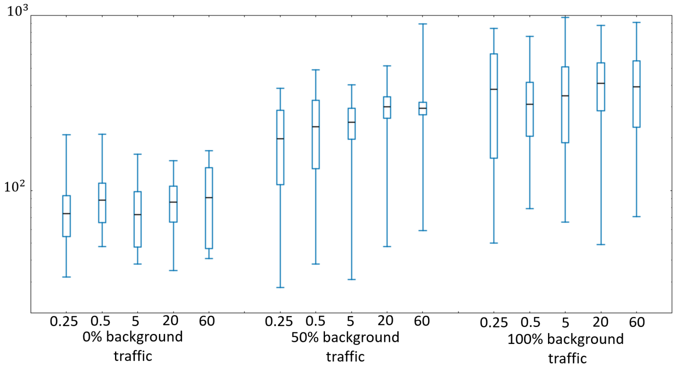

Fig. 4. Packet delays [ms] on Cat 3 traffic, -100 dBm

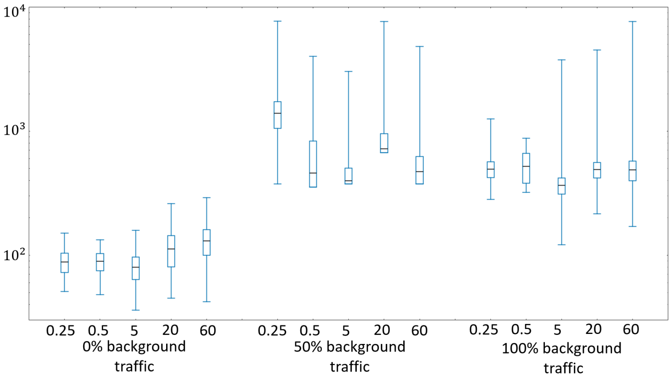

Fig. 5. Packet delays [ms] on Cat-M1 traffic, -60 dBm

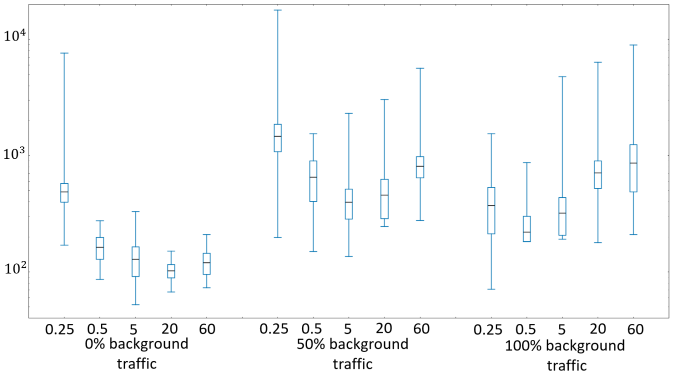

Fig. 6. Packet delays [ms] on Cat-M1 traffic, -100 dBm

6. However, in case of any background traffic, it increases dramatically, even up to several seconds. Cat-M1 devices were unable to connect when the signal level was around -115 dBm. The cloud-to-cloud communication here is also determined by the uplink peak data rate of each device. Based on the comparison in case there is any background traffic on the cell, the delays will go up at least 100 ms, and the expected value can be around 1000 ms.

C. Evaluation of NB-IoT measurement

The measurements show the latency and its fluctuations using NB-IoT on the network concerning signal strength and background traffic. Figure 7 with -60 dBm shows that in case of excellent signal strength how the transmission delay varies with the background traffic. Figure 8 for -100 dBm and Figure 9 for -115 dBm clearly show the individual behaviour of NB-IoT, where the device was able to connect to the network and transmit data beside weak signal strength. At this signal level, the Cat-M1 and Cat 3 devices were unable to connect. As it can be seen, at least one of the ”prices” of the connectivity is definitely the high latency. However, the results of the Figure 9 for 100% background noise are more than impressive. It shows that for terrible coverage, the delays are reducing and obviously smaller. The results can be explained based on the user session establishment [12] call flow, and based on the settings of the 4G eNodeB and the UE. The user equipment establishes or closes the communication with the eNodeB, and it requires to activate and then release the Radio Link Control (RLC) Channel. These require control communication between the eNodeB and UE, and it also takes some time. However, the latency also affects the signalling communication, not just data transmission. In result, the RLC is not released after sending each data packet, so there will be no need to establish the data channel for communication again. This behaviour leads to faster data communication. Based on the measurements, it can be seen that although the loss of the data transmission is close to 0, the delay can take several minutes in specific situations. However, it is essential to mention that even in case of heavy background traffic, it was able to send messages.

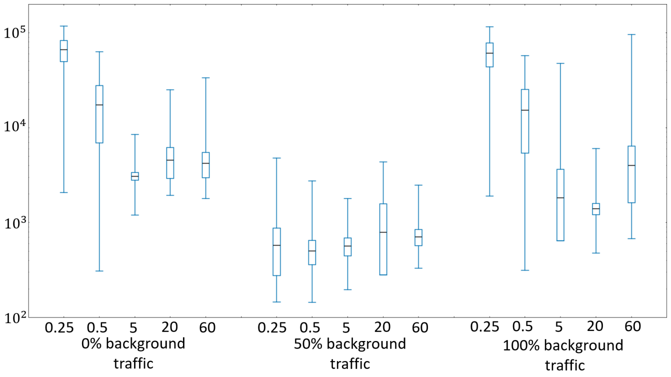

Fig. 7. Packet delays [ms] on NB-IoT traffic, -60 dBm signal strength

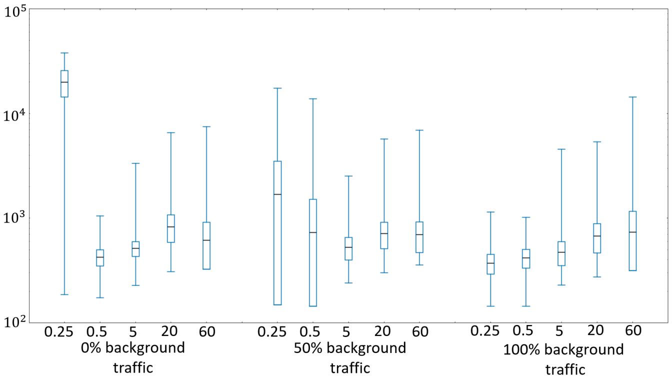

Fig. 8. Packet delays [ms] on NB-IoT traffic, -100 dBm

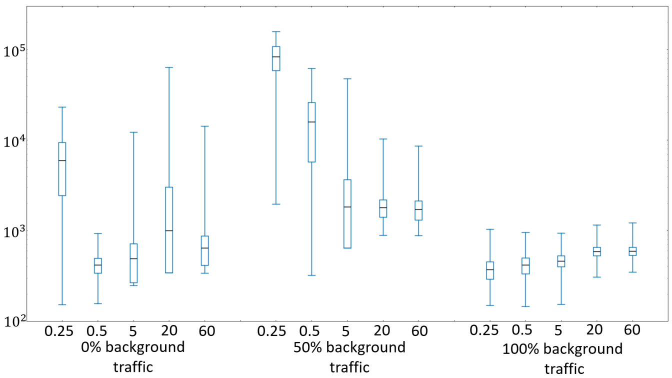

Fig. 9. Packet delays [ms] on NB-IoT traffic, -115 dBm

VI. CONCLUSION

Within the automation clouds of IIoT, communication is usually local, using wired and wireless technologies as well. However, for inter-cloud information exchange, it is recommended to examine external access techniques which allow greater transmission distance. From the services point of view, the critical parameters are mostly usage- and area-specific.

Following the identified challenges, the article briefly presented the Arrowhead Framework, which allows inter-cloud secure, and QoS-aware communication among local IoT clouds. As the main topic of the paper, it presented a measurement methodology which demonstrates how the end-to-end communications can be provided with the currently available MTC related access technologies. It also demonstrated that collaboration between different CPSs could be achieved, using the presented SOA compatible Arrowhead Framework. The evaluation of measurements can be a sound basis for scaling industrial communication networks in line with the exemplary industrial networking use cases, where data transmission needs to meet higher requirements, and the background traffic should be taken into account for reliability and data loss.

There are many ways to continue the work. In one hand, to continue the examination of external communication opportunities. On the other hand, a much larger task is the analysis of local, internal communication, mapping with the industrial requirements, and validate the available technological solutions, taking into account such industrial scenarios, where the role of latency is even more critical.

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