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## RESEARCH ARTICLE

# Wireless Communications for Internet of Farming: An Early 5G Measurement Study

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**ABSTRACT** Data-driven agriculture and Internet of Farming (IoF) require reliable communication systems. Nowadays, only some of the key use cases demanded by the agricultural industry verticals get support from multiple state of the art wireless technologies such as 4G, Wi-Fi, or Low Power Wide Area Network (LPWAN) technologies, combined with satellite and cloud access. However, the ones demanding very high data rates or very low latency are still not feasible. With 5G, designed for flexible support of Extreme Mobile Broadband (xMBB), Massive Machine-Type Communications (mMTC) and Ultra-reliable Machine-Type Communications (uMTC), more agricultural use cases will be possible. This paper provides a reference list of data-driven agriculture scenarios and use cases with their associated communication requirements, and whose feasibility is evaluated in a live 5G trial performed in a representative rural area scenario in the south of Denmark. The paper details a reference methodology for assessing 5G Quality of Service (QoS), including multi-connectivity schemes and reports the empirical 5G performance results, which are put in perspective of the requirements for the different IoF reference scenarios. The empirical results indicate that early 5G deployments are already capable of reliably serving data-driven agriculture vertical use cases such as those related to agricultural logistics or configuration of machinery and diagnostics in 65.8-99% of the cases; but it will be necessary to wait for 5G network upgrades and coming 5G Releases in order to operate the more low latency demanding use cases.

**INDEX TERMS** IoF, data-driven agriculture, 5G, quality of service, multi-connectivity, live measurement trial.

## I. INTRODUCTION

The demand for smarter and more efficient agriculture is on a never-ending rise as farmers seek to maximise yields and minimise costs. Agricultural businesses seek to source high quality agricultural production, taken to market efficiently, and of sufficient quantity to sustain their market and profits, as well as to minimise the environmental footprint of their supply chain and operations. In this respect, according to the International Food Policy Research Institute, data-driven

techniques can support the agricultural and food sectors to achieve the expected doubling of demand for food by 2050 by increasing farm productivity by as much as 67% and cutting down agricultural losses [1]. The size, scale, and unstructured nature of future data-driven agriculture and Internet of Farming (IoF) require the usage of new analytical tools and frameworks to be developed and employed. These frameworks need to be flexible enough to weave together data from millions of hectares and from various sources, such as weather data, yield data, satellite imagery, small unmanned wireless sensor networks, aerial imagery, planting prescriptions, embedded intelligence in equipment, and equipment

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diagnostics [2]. Once in place, these solutions enable the creation of predictive modelling and better models to manage crop failure risk and to boost efficiency in crop production [3], [4]. Hence, data-driven agriculture is a driver to provide predictive insights to future outcomes of farming, drive real-time operational decisions, reinvent business processes for faster innovative actions and game-changing business models [5]. If these goals are achieved, it has the potential to be the next agricultural revolution of smart products utilizing precision application of inputs, yield monitors, and other site-specific sensors to a point where the system can be evaluated as a whole.

Within this context, mobile technology is increasingly leading to the creation of innovative services and applications that are used throughout the agricultural value chain to help farmers make the most of the resources available to them. Considering just one example, field trials have shown that techniques that use sensor measurements to apply site-specific amount of irrigation water can maintain yield while reducing the water intake by 32% on a regional scale and on field scale by 25% [6], [7]. Similar techniques to vary other farm inputs like seeds, soil nutrients, etc., have proven to be beneficial [8], [9]. The advent of aerial inspection systems [10], [11] has enabled agricultural advisory services and Farm Management and Information Systems (FMIS) to get richer sensor data. Over time, all this data can indicate useful practices in farms and make suggestions based on previous crop cycles; resulting in higher yields, lower inputs and less environmental impact. A key challenge in many locations for the further development of data-driven agriculture is the lack of seamless connectivity [12]. Without ubiquitous network availability, the agricultural sector falls at risk of not progressing at the same pace other more digitized industries do, causing an impact not only on the supply chain, but also on the overall customer satisfaction [13].

Therefore, the IoF and data-driven agriculture are about connectivity. Beyond the introduction of new tools and practices, the real promise of data-driven agriculture in terms of productivity increase, resides in the ability to remotely collect, use, and exchange data. Without sufficient wireless data transfer service, automated real-time communication between farm equipment and online servers is not possible, forcing producers to rely on manual data transfer, which may not happen until after the season is over. By then, opportunities to adjust management practices are missed, significantly affecting farm profitability, productivity, and environmental benefits. In addition, agricultural areas that lack adequate connectivity may lead to geospatial data not being sufficiently backed-up in a timely manner, therefore increasing the risk of this valuable data being lost or destroyed [14]. In this respect, agricultural areas are slowly benefiting from the evolution of communication technologies. The advent of the Internet of Things (IoT) came with associated development of new solutions based on Low Power Wide Area Network (LPWAN) technologies which, together with Wi-Fi, satellite, and cellular 4G communications, are the main connectivity options

applied to smart agriculture applications nowadays [15]. This set of available communication technologies will be complemented with 5G. By design, 5G technology will be capable of providing higher capacity, higher data rates, lower latency, and increased energy efficiency than previous generations of mobile cellular technologies. Therefore, 5G is expected to be an enabler for more flexible and efficient solutions for smart farming [16].

The research presented in this paper aims at exploring the applicability of 5G technology to the IoF and data-driven agriculture. To do this, a number of relevant technology use case scenarios with emphasis on farm machinery are defined and described together with their associated connectivity requirements. The feasibility of operation of these use cases over 5G is evaluated based on the empirical results obtained in an extensive live 5G trial that was carried out in a representative agricultural area in the south of Denmark. Further, a reference methodology to accurately measure Quality of Service (QoS)-related parameters for evaluation of 5G performance in a data-driven agriculture context was developed. The main contributions of this paper are listed as follows:

- Reference list of data-driven agriculture scenarios and use cases and related communication requirements.
- Summary of the state of the art in communication technologies for data-driven agriculture, including current 5G perspectives.
- Reference methodology for measuring 5G QoS in the context of data-driven agriculture, including multi-connectivity schemes.
- Report and discussion of results from an early 5G trial with focus on data-driven agriculture scenarios, including an overview of the current suitability of early 5G networks for operating advanced agricultural use cases.

The rest of the paper is structured as follows: Section II addresses the definition and characterization of data-driven agricultural scenarios, and surveys the state-of-the-art communication technologies applied to agricultural operations. Section III describes in details the development of the 5G QoS measurement framework, together with the measurement equipment and scenario considered in the live 5G trial. Section IV details the 5G measurement results with focus on the relevant QoS parameters for evaluation of the suitability of data-driven agriculture use cases. Section V presents an analysis of the 5G trial results and elaborates on the current capabilities of early 5G deployments to provide data-driven agriculture and IoF services. Finally, Section VI concludes the paper.

## II. DATA-DRIVEN AGRICULTURE AND TECHNOLOGY VERTICALS WITH EMPHASIS ON AGRICULTURAL APPLICATIONS

Table 1 describes relevant technology verticals in the arable sector within the context of data-driven agriculture with emphasis on farm machinery [17]. The scenario applications and immediate technological trends have been compiled using mainly inputs from the IoF2020 project [18],

**TABLE 1. Classification of data-driven agricultural verticals with emphasis on farm machinery.**

Technology vertical / Scenario class	Specific functionalities
1.1 Machine and data center/server exchange of data, pre- and post-operational	Machines for field operations need to exchange data with remote servers or data centers. For example, maps, commands, field jobs, documentation, and decision strategy are sent to machines to respond in the forward link (download) and multi-source data are collected and feedback to the server through the backhauling link (upload).
1.2 Machine and data center exchange of data in real time	The server is able to access a data recorder from e.g., the Electronic Control Unit (ECU), sensors and digital cameras, such that the performance and status of the machinery can be monitored. As a result, for example, the update of route plan, application maps, machine settings, and receiving weather data for spraying and harvesting, can be done by wireless link in a near real time manner.
2.1 Vehicles platooning for joint operation	Enable the tractors/agricultural vehicles with different tasks to dynamically form a grouped operation together. All the machinery in the platoon receive periodic data from the master machine or application servers to carry out platoon operations.
2.2 Cooperative safety	Enable safer driving, collision avoidance, and improved production efficiency. Each vehicle and/or infrastructure shares data obtained from its local sensors with vehicles in proximity, and that allows vehicles to coordinate their trajectories, manoeuvres or operations.
2.3 Extended sensors for cooperative perception	Enable the exchange of raw or processed data gathered through local sensors, live video data from on-board cameras, and maps, tasks among machinery, infrastructure, and remote application servers. The purpose is to enhance the perception of machinery environment beyond what the machinery own sensors can detect and have a greater view of the local situation.
2.4 Remote driving and control	Enable an application interface on PC or smart device near the agricultural vehicle/machinery to operate a remote machinery/vehicle for production.
2.5 Logistics	High update frequency of route plan, navigation points, bin level, positions, etc. The representative applications are optimisation of field operations.
3.1 M2M data exchange and control	Farm machines exchange data directly, such as status, settings, configuration/control, tasks, and maps. For instance, an interesting application is the exchange of route planning and maps between manned vehicles and autonomous vehicles in different arable fields. This data exchange does not need the aid of a gateway or infrastructure. Another category is on board Wireless ISO-bus communication, ISO-bus terminal to ECUs.
3.2 Extended machine vision	A machine vision system is typically not communicated on the vehicle CAN-bus. Hence, such operation is required as it can extend machine vision systems on vehicles by using wireless communication of machine vision data to on-board ECUs.
4.1 Smart device to machine exchange of data	Smartphone and tablet can access the machine to upload and download prescription maps, downloading as-applied maps, images, data files, etc.
4.2 Smart device to machine configuration and diagnostics	Access to e.g. ISO-bus terminals for configuration of the machine or implement settings directly on ECU. Monitoring of machine performance in real-time and logging of vehicle/machinery data.

**TABLE 2. Communication performance requirements and service types for the identified data-driven agricultural verticals.**

Agricultural machinery vertical classes	Link latency/cycle time [ms]	Reliability/PER	Data rate [Mbit/s]	Typical block size [bytes]	Expected communication range [m]	Service type
1.1	100 (RTT)	$10^{-2}$ (1%)	50	1500	250	xMBB
1.2	50 (UL OWD)	$10^{-2}$ (1%)	100	1500	3000	xMBB
2.1	10 (RTT)	$10^{-3}$ (0.1%)	1	100	1000	uMTC
2.2	10 (RTT)	$10^{-4}$ (0.01%)	5	500	2000	uMTC
2.3	10 (RTT)	$10^{-3}$ (0.1%)	100	1000	3000	uMTC
2.4	10 (RTT)	$10^{-5}$ (0.001%)	1	100	250	uMTC
2.5	100 (DL OWD)	$10^{-2}$ (1%)	0.5	50	3000	mMTC
3.1	100 (RTT)	$10^{-2}$ (1%)	5	100	3000	xMBB
3.2	100 (UL OWD)	$10^{-2}$ (1%)	100	1500	50	xMBB
4.1	100 (DL OWD)	$10^{-2}$ (1%)	10	100	3000	xMBB
4.2	100 (RTT)	$10^{-2}$ (1%)	1	100	50	mMTC

together with extensive desk research and industry statements (e.g., online information); resulting in a classification with four different classes of vertical scenarios, with the different

sets of operations and actors for data-driven agriculture and farm machinery. Each scenario represents the specific functionality or operation in a different context (i.e., actors,

machines, field environment, level of automation and timeliness, etc.). The identified scenario classes are: 1) machine and server data exchange, 2) connected agricultural vehicles, 3) farm machinery direct communication, and 4) configuration and diagnostics.

Table 2, provides a summary of key performance communication requirements associated to the identified data-driven agricultural verticals and classes. The considered requirements are link latency stated as One-Way Delay (OWD) for those classes relying mainly on the Upload (UL) or Download (DL) of information, or control cycle time stated as Round-Trip Time (RTT) for those classes where there is a tighter real-time communication need including, e.g., closed-control loops of industrial machinery, where a sensor/actuator pair is controlled remotely from a centralized cloud server. Other considered reference requirements are reliability stated as the maximum probability of failure or Packet Error Rate (PER), effective data rate and block size to get an indication of the amount of data to be transferred, expected communication range, and network speeds needed to be supported by the wireless communication links for the different classes. Finally, for further reference, the different scenario classes are categorized according to the three main service types, defined by the International Telecommunications Union (ITU) [19]:

- Extreme Mobile Broadband (xMBB), often also referred to as enhanced MBB (eMBB), requiring both extremely high data rates and low-latency communication in some areas, and reliable broadband access over large coverage areas.
- Massive Machine-Type Communications (mMTC), requiring wireless connectivity for up to one million of network-enabled devices per cell. Scalable connectivity for an increasing number of devices, wide area coverage, and deep indoor penetration are key priorities.
- Ultra-Reliable Machine-Type Communications (uMTC), requiring ultra-reliable low-latency and/or resilient communication links for, e.g., Vehicle-to-Anything (V2X) communication and industrial control applications.

These considered technology verticals and scenario classes, and their associated communication requirements will be used as a basis for the discussion of the results from the 5G field evaluation results reported later in the article.

#### **A. STATE-OF-THE-ART IN COMMUNICATION TECHNOLOGIES FOR DATA-DRIVEN AGRICULTURE IN RURAL AREAS**

As described in the specific functionalities for the considered technology verticals and scenario classes, the IoF and the data-driven agriculture strive for IoT and Machine-to-Machine (M2M) communication technologies to interconnect sets of farm machines and FMIS in defined cropping areas [20]. Additionally, ultra-reliable and low latency connectivity (URLLC) is required for M2M systems serving diverse applications including sensing, monitoring, and remote control, i.e. emerging technologies as autonomous

vehicles, digital monitoring of animal husbandry, weed and crop species identification. These represent use cases belonging to the next generation network services, which push the specifications of telecommunication standards and technologies in multiple aspects such as data rate, latency, reliability, device/network energy efficiency, mobility, and connection density. A key challenge in many locations for the further development of data-driven agriculture is the lack of connectivity, that is, poor coverage or system availability. At these locations, satellite communications [12] or LPWAN technologies like LoRa, Sigfox, LTE-M, or NB-IoT provide a real opportunity to overcome such limitations [21], [22], [23], at the cost of limited data rate availability. While the LPWAN and satellite technologies are ideal for IoT-enabled agricultural technologies, transmitting small packets of sensory data, they are not designed to handle the bandwidth requirements of verticals such as voice, imaging, and video transmission. These use cases can be enabled through on-farm Wi-Fi networks [24].

The combination of these technologies with the high speed cellular ones, such as 4G LTE, are slowly transforming wireless connectivity into an ubiquitous, omnipresent service. 4G LTE has greatly increased the available capacity over previous network generations, enabling a wide swath of new use cases for network operators, technology providers, and consumers. This includes multimedia streaming of high definition audio and video [25], making already feasible some of the xMBB and mMTC use cases listed in Table 1 for data-driven agriculture and smart farming that require more intelligence, higher data transmission speed, scalability, secure communication capabilities and processing power to perform heavy computational tasks and run loaded services. However, even though the 4G LTE network offers high speed and good connectivity, it does not have the necessary flexibility to provide reliable connectivity to all scenarios, specially the uMTC cases. These limitations of the current generations of cellular networks will be overcome by transitioning to the next generation, 5G NR, which has been conceived from its early design as an advanced and flexible wireless technology able to cope with the most challenging use cases from all three service types [19], [26]. With 5G NR, seamless communication for machines and devices will be possible, allowing for new relevant applications for the IoF, such as high resolution video streaming, telemetry operations, smart logistics, and real-time remote control [16].

#### **B. EARLY 5G RELEASES AND DEPLOYMENTS IN RELATION TO DATA-DRIVEN AGRICULTURE**

With the new capabilities of 5G, telecom operators intend to improve the user experience of existing mobile customers, while enabling cloud connectivity and targeting new business opportunities and use cases such as manufacturing and agricultural industries [27]. In order to achieve this, the main design development of 5G has focused on bringing down latencies to the millisecond level in order to support real-time wireless control loops while also improving the overall

network capacity to support more connected devices than previous technologies.

Of special interest for industrial and agricultural users are the new options for network slicing in 5G. This makes it possible for a farming or agricultural private company to buy customized 5G cellular services from a telecom operator adapted to their specific use cases. Such network slicing services are provided by the operator from their public infrastructure, but using dedicated resources that are not shared with other cellular users in the area, thus, guaranteeing the necessary reliability and QoS levels [28]. Additionally, 5G also enables the possibility of deploying completely private networks operated by a private company or community of farmers within a specific area, e.g., crop fields, factory, processing building, etc. Such private option comes with the associated potential benefit of enabling extra low latencies as compared to the network slices [29]. However, the deployment and operational costs are much higher in the private case as they require the installation of dedicated infrastructure and the leasing of 5G spectrum from the national regulator (or sub-leasing from a given telecom operator).

Presently, 5G is being rolled out in countries all across the globe and consumers can already purchase mobile phone subscriptions which give access to the new services. However, it is still the early days for 5G and the technology is still immature. 5G deployment is done in rolling manner, where features are piecemeal rolled out as they become available. This is done in releases (Rel.), where the initial 5G one is Rel.15 implementing the new wireless waveform for 5G connectivity together with its integration with 4G LTE networks and basic features such as increased data rates [30]. This means the current early 5G systems might not yet provide many of the promised features and benefits, which will come later with Rel.16 (expected to be commercially available by the end of 2023) with ultra-low latency features, and Rel.17, which will enable positioning over 5G [31].

During initial roll-out, mobile operators focus on 5G NSA (Non Stand-Alone), which is a stopgap technology between existing 4G deployments and full-blown 5G SA (Stand-Alone) [32]. 5G NSA allows operators to upgrade their existing 4G infrastructure with 5G, offering regular voice and text services over 4G, while taking advantage of the initial 5G features to provide improved throughput to those users with 5G subscription capabilities. Once the infrastructure is fully ready, after the initial roll-out, operators are expected to switch to 5G SA (only software upgrades will be needed), enabling the full commercial potential of 5G for their users.

### III. 5G MEASUREMENT METHODOLOGY

Specific 5G QoS testing methodology and testing equipment and setup were developed. The testing methodology was based on the previous cellular network characterization work done by the authors in [33], while the dedicated equipment was build on top of the reference design (originally designed for 5G Industry 4.0 manufacturing applications) reported by the authors in [34]. In order to empirically assess the 5G

network capabilities, the primary focus was the implementation of a measurement device able to monitor and record the relevant communication QoS parameters: link latency, PER, and throughput (data rate). For further reference, the device was designed to also record timing, Global Positioning System (GPS) position, and 5G signal strength (as received power in dBm), and 5G signal quality in terms of Signal-to-Noise Ratio (SNR). Recording and analyzing all these parameters over a specific measurement route, allows for direct assessment of the 5G capabilities for providing data-driven agriculture services in a given area by direct comparison with the values previously reported in Table 1. This is also enabled by the fact that the overall setup and flows of data in the test resemble the main IoF system architectures, where different application end-point farm machines collect and send/receive data via wireless Internet connection to a cloud-based server.

Under these flow considerations, the considered measurement setup consists of two end-points, as illustrated in Figure 1: a 5G-capable user test device, which also serves as measurement device, and a dedicated cloud server hosted by Aalborg University and accessible via Internet (located in Aalborg, Denmark, approximately 250 km from the location of the test). All measurements were performed between these two devices, meaning that the data traffic from the 5G user device to the cloud server will traverse the 5G radio network, then the 5G core network and Internet Service Provider (ISP)'s backbone (located in Copenhagen, 300 km from the location of the test), then the general Internet, and finally the Aalborg University intranet. Effectively, the measurements include combined communication effects from both the wireless 5G network, the fixed network infrastructure, and also server processing performance impact; shedding some light on the end-to-end performance of cloud-based agricultural systems.

The 5G measurement setup was further designed to support advanced multi-connectivity, which is a simple connectivity solution based on hardware duplication that might be of interest for farming and agricultural technology verticals requiring reliable wireless support for their industrial applications. Multi-connectivity is implemented by considering two 5G network modem interfaces (instead of a single one as is normally done) at the user device in order to increase the availability and reliability of the 5G connection by using the best of the two or a combination of both. Multi-connectivity schemes, rely on the uncorrelation in time and space of poor network performances or failures on the different interfaces [33]. This means than when one of the interfaces might be experiencing long delays or transmitting low data due to high number of connected users, long distance to the serving cell, or is performing a cell change; the other might be connected to a nearer different cell and, thus, experiencing a better connection enabling the possibility of having better latency or higher data rate transmissions. Hence, the methodology developed for assessment of the suitability of 5G for data-driven agriculture and IoF will consider not only the standard 5G user performance, but also the one that could

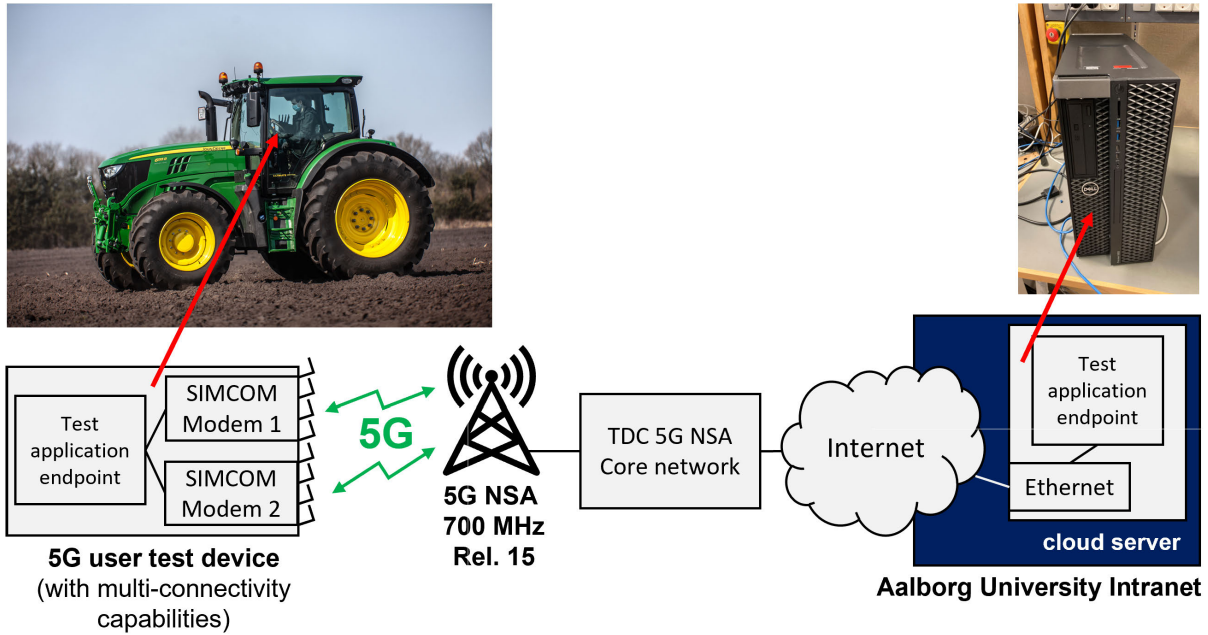


FIGURE 1. 5G IoF trial test setup architecture including data transmission flows between the 5G test device and the cloud server.

be experienced by industrial multi-connectivity receivers, such as [35].

**A. 5G TRIAL TEST SITE DESCRIPTION**

The scenario selected for the data-driven agriculture and IoF 5G trial was an area representative of typical agricultural fields with nearby roads access near Padborg, in the south of Denmark, close to the German border. In this area, there was 5G coverage from the Danish telecom operator TDC. This 5G network was selected based on the fact that TDC has already reported 5G coverage in 98.4% of the country, including main rural areas [36], while other operators are still working towards rolling-out 5G in the country side [37]. At the moment of the trial, TDC’s public 5G network was an early deployment of 5G NSA, operating in Time Division Duplex (TDD) mode over 100 MHz bandwidth in the 700 MHz band, using 1800 MHz as 4G LTE anchor band. This means that the network was not yet able to provide the full feature set of 5G such as extreme throughput, ultra-low latency or Device-to-Device (D2D) communications. As the trial was done right after the initial roll-outs, no impact from other simultaneously-connected devices was expected; as still not many TDC public network users had 5G capabilities yet. Thus, the reported results can be seen as those expected by industrial farming or agriculture companies operating over a dedicated 5G network slice deployment.

In order to evaluate the 5G QoS parameters in the test scenario, the measurement route illustrated in Figure 2 was defined. Such route represents the expected environment where farming equipment is expected to be used and was planned to include a mixture of realistic environments, with

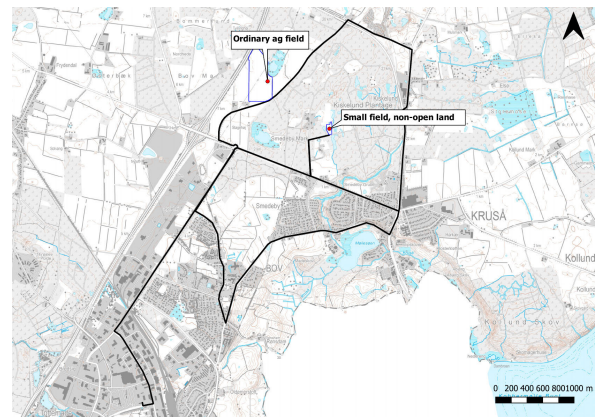
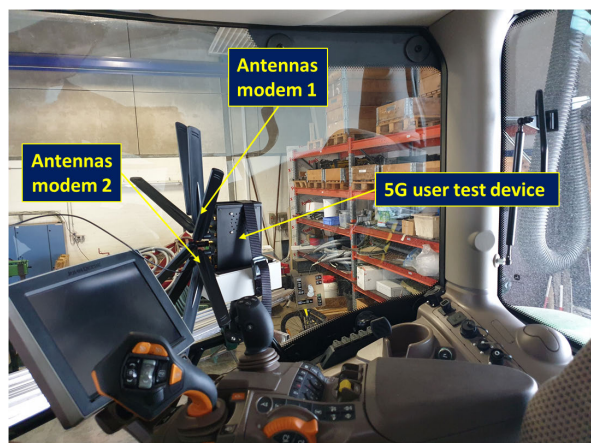


FIGURE 2. Map of the 5G IoF trial scenario and measurement route.

both on- and off-road driving. The roads were primarily small to medium size country roads, while the off-road driving consists of driving on an open agricultural field and inside a forest. The telecom operator TDC provided coverage information prior to the trial, confirming the availability of 5G coverage throughout most of the track. However, certain areas, and more specifically, the forest, were expected to be slightly challenging. The route, with a total length of approximately 22 km (4 km off-road, 18 km on-road), and an altitude variation of 18-52 m, was driven twice using the John Deere 6155R tractor [38] displayed on the top left in Figure 1 at an average speed of 40-50 km/h when on-road and approximately 10 km/h when off-road. This was done to expose the 5G equipment in a realistic environment and measure the 5G farming system end-to-end performance under these conditions.



**FIGURE 3.** Picture of the customized 5G measurement device installed inside the cabin of the tractor.

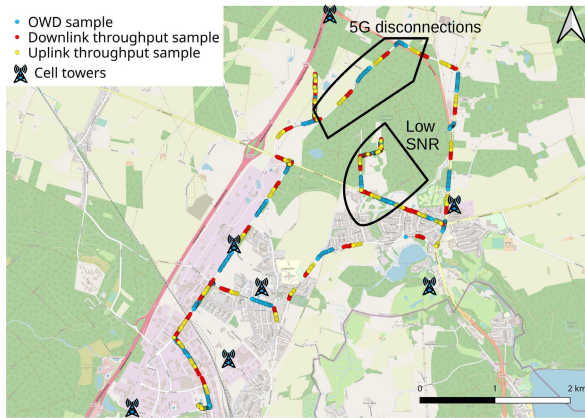
### B. 5G MEASUREMENT SETUP

The developed 5G measurement device was installed inside the cabin tractor, as generally displayed in top left in Figure 1, and in details in Figure 3. The baseline platform is an ARM-based Gateworks GW6405 industrial computer [39], chosen due to its small size, support for up to four mini-PCIe extension cards and integrated GPS hardware with Pulse Per Second (PPS). This GPS hardware allows recording the position of any given 5G measurement sample and also having easy access to an accurate time source for synchronization. By using the LinuxPPS API it is possible to synchronize the industrial computer clock with down to 10-100  $\mu$ s accuracy [40]. The computer board is housed in a metal enclosure and equipped with 8 omnidirectional antennas, feeding two Simcom SIM8300G-m2 cellular modems [41] (with four antenna ports each) installed in the GW6405's mini-PCIe slots through an M.2 to mini-PCIe converter board [42]. The SIM8300G-m2 is chosen based on recommendations from TDC as it supports both their 4G and 5G sub-6 GHz bands. A GPS antenna is connected to the GW6405 and routed to the roof of the tractor. At the Aalborg University server side, the server was a generic x86 PC running Ubuntu. The server PC, displayed on the top right in Figure 1, is connected to the Aalborg University intranet network through a 1 Gbit/s Ethernet connection, and its clock is synchronized against an on-premise time standard reference device, which in turn is synchronized via GPS. This means that both ends in our 5G measurement setup are fully-synchronized, allowing for accurate link latency measurements.

### C. 5G MEASUREMENT PROCEDURES AND DEVICE CONFIGURATION

In order to evaluate the 5G system performance, the developed 5G multi-connectivity device installed inside the tractor communicates with the remote server, emulating a data-driven agriculture cloud application. The QoS indicators measurement procedures and the implementation of performance estimation of the multi-connectivity schemes was done as follows:

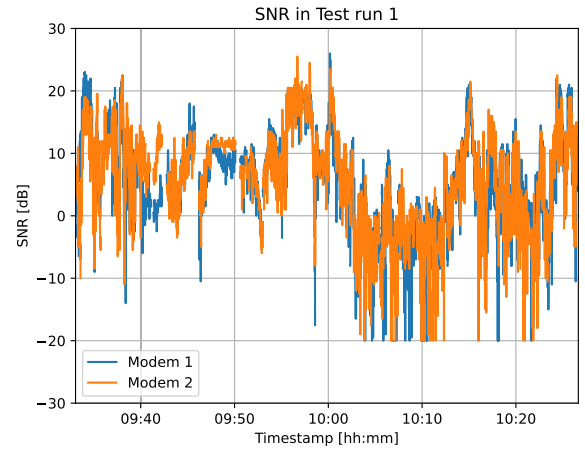
- **Link latency:** communication delay is measured in a real-time context by adapting the framework in [33]. As both ends (5G end device and cloud server) are time-synchronized, both OWD and RTT accurate measurements are possible. OWD is measured by transmitting timestamped UDP packets between the two hosts, and then calculating the time difference between time of transmission and time of reception. This is done in both communication directions: downlink (DL) from server to end device, and uplink (UL) from end device to server. For a given sample  $i$ , RTT is later estimated by combining consecutive DL OWD and UL OWD values ( $RTT_i = OWD_{i,DL} + OWD_{i,UL}$ ), providing a performance reference time value for a potential control cycle. OWD and RTT are independently estimated for each of the two 5G interfaces on the 5G device side. As both modems always transmit packets in lock-step, it is possible to evaluate a multi-connectivity scheme making use of the best of the two interfaces (i.e., the one that experiences lower latency), by selecting the lowest OWD for a given packet. This means that for each packet ( $p_i$ ) sent on modem interface 1 ( $p_i^1$ ), a twin packet ( $p_i^2$ ) was sent on modem interface 2. This produces two OWD samples ( $OWD_i^1$ ) and ( $OWD_i^2$ ), making it possible to estimate a OWD multi-connectivity sample as  $OWD_i^{MC,min} = \min(OWD_i^1, OWD_i^2)$ . In the multi-connectivity case, RTT is estimated by combining consecutive consecutive DL OWD and UL OWD multi-connectivity samples ( $RTT_i^{MC} = OWD_{i,DL}^{MC,min} + OWD_{i,UL}^{MC,min}$ ). The OWD measurement application is configured to transmit 1000 UDP packets with a size of 300 bytes at an interval of 25 ms between packets. At the device side, the 1000 UDP packets are sent on both 5G interfaces synchronously. The server is configured identically and will transmit the same amount of packets from the server to the two 5G interfaces on the device once the test was initiated.
- **PER:** reliability or probability of failure is also estimated from the communication delay measurement. Apart from time-stamps, the transmitted UDP packets include an incremental counter-based packet ID, which allows for easy detection of lost packets for the different configurations and schemes in both DL and UL directions.
- **Throughput (TP):** effective application layer data rates are also measured for the different schemes in both DL and UL directions by means of the iperf3 application [43]. The server computer runs two server instances of iperf3 and the 5G end device launches one iperf3 instance per 5G interface. The throughput tests for DL and UL are run separately and lasts 10 s each. The throughput tests are full-buffer tests and will attempt to saturate the 5G links by sending approximately 500 Mbit/s on the different interfaces. During a 10 s throughput test, iperf3 reports the throughput at 1 s



**FIGURE 4.** Map of the 5G IoF trial scenario illustrating the interleaved QoS data collection.

intervals, resulting in 10 data rate samples. Here two multi-connectivity schemes are evaluated. The first one, relates to the latency multi-connectivity one, exploiting the best of the two interfaces, and thus experiencing the highest data rate of both interfaces. This means that for each throughput test ( $TP_j$ ), where two measurement samples are obtained, one for interface 1 ( $TP_j^1$ ) and one for interface 2 ( $TP_j^2$ ), the performance of this multi-connectivity scheme can be estimated as  $TP_j^{MC,max} = \max(TP_j^1, TP_j^2)$ . The second multi-connectivity scheme resembles the case where the main interest of the end user is, not on using the best interface but, on achieving higher data rates than with a single interface. In this case, the device will use both interfaces 1 and 2 to transmit/receive different data in a coordinated way, and its performance, based on the throughput samples, can be evaluated as  $TP_j^{MC,sum} = TP_j^1 + TP_j^2$ .

Link latency and throughput measurements are done in a time-interleaved manner. This is done to ensure an unbiased emulation of a farming application and a fair utilization of the network during the tests (running all tests in parallel will result in a non-realistic saturation of network load and interfaces). The measurements were controlled by a bash script which switches between the different measurements in an infinite loop. A measurement loop consists of OWD measurements (including RTT and PER estimation, and multi-connectivity evaluation), DL throughput and UL throughput measurements (including multi-connectivity evaluation). The data recorded in each loop is stored on to non-volatile memory and assigned a sequential run number. While the QoS measurements are performed, modem status information was simultaneously collected (for both modems) and the current GPS timing and location. The modem status includes information such as signal quality, which cell the modem currently is connected to, and which cellular technologies are currently active. With these settings, a test loop is typically completed every 60 s, when factoring in application launch times, processing times, and varying network conditions.



**FIGURE 5.** Trace of the SNR over time experienced over the measurement route.

Figure 4 illustrates how the gathered interleaved measurement data was distributed along the route together with the position of TDC's 5G base stations in the area. A single drive of the route took about 50 min. As the route was driven twice, the overall measurement time was approximately 100 min. In total, approximately 100000 OWD samples in DL/UL (blue dots), 1000 DL throughput samples (red dots), and 1000 UL throughput samples (yellow dots) were collected for analysis.

## IV. RESULTS

### A. 5G COVERAGE AND SIGNAL QUALITY

The 5G coverage in the test area was analyzed based on the signal quality measurements. Figure 5 shows the SNR measured by the two modems throughout the first test drive. It is noted that both traces follow a similar trend for both modems, indicating that they have probably been connected to the same cells during most of the route, especially in the second part of the route after 09:50. However, it clearly comes to attention that there are instantaneous differences throughout the entire route. This illustrates exactly the expected network uncorrelation behavior, previously described in Section III, that can be exploited by multi-connectivity schemes to increase the reliability of the communication.

It is also observed that, at several periods (i.e., around 09:43, 09:46 or 09:50), some data is missing. This indicates a loss of the 5G connection. Those periods of time where there was a loss of 5G connection corresponded mainly to driving in an elevated area where the coverage levels from multiple nearby and far off 5G base stations were comparable, so the modems performed a number of consecutive handovers between cells, slightly interrupting the 5G test data transmission/reception. Also, a noticeable dip in SNR was detected in the time period between 10:00 and 10:15, which corresponds to the part of the route which led through a forest area. According to TDC's coverage maps, this area was expected to have poor 5G coverage, which matches with our observation. However, while the signal quality was poor,



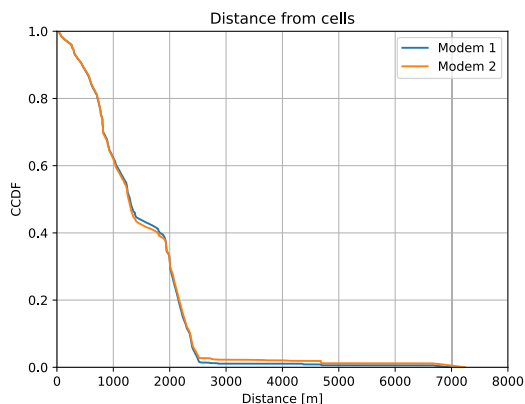


FIGURE 6. CCDF of the distance from the cells during the test drives.

the modems were still able to maintain a 5G connection. Both areas have been marked in the map in Figure 4.

In 5G NSA networks, client devices will idle on 4G and only connect over 5G when an active data transmission or reception takes place. As our test made active use of data during the link latency and throughput measurements we ensured connectivity to 5G, in those areas with 5G coverage, during most of the test. From the analysis of the modem logs, it was observed that, through the entire measurement route, modem 1 and modem 2 operated over 5G during 96.7% and 96.1% of the time, respectively. The remaining 3.3% of the time for modem 1 and 3.9% of the time for modem 2, connectivity was over 4G. This mainly happened in those areas where 5G signal quality was too poor and the modem has opted to use 4G instead to guarantee a successful connection.

By looking at the recorded GPS positions and analyzing to which cells the modems were connected, it was possible to calculate the distance of the active 5G end device to the 5G serving cell, which gives further idea of the coverage, and also of the density of the 5G TDC deployment in the IoF test area. A Complementary Cumulative Distribution Function (CCDF) plot of the distances between 5G device and serving cell is given Figure 6. Both modems exhibit a similar trend, due to the fact that they both have probably been connected to the same cells during most of the route, as also observed in Figure 5. The 5G modems were connected to cells that are less than 3 km in 99% of the cases. Connections to the furthest cells (up to 7 km) only happened in the specific area of the route where the few disconnections happened.

**B. 5G LINK LATENCY PERFORMANCE**

The link latency performance was individually evaluated for DL and UL in terms of OWD, and combined in terms of RTT. Figure 7 displays the CCDF of DL OWD, illustrating a very similar behavior for both modem 1 and modem 2, with a median ( $10^{-0.5}$ ) DL OWD of 11.5 ms and 12.1 ms, respectively; with a DL OWD lower than 100 ms in 99.3% of the cases. The tails of the distributions are slightly different between modem 1 and modem 2, reaching in both cases a maximum DL OWD of approximately 0.5 s at the 99.999%

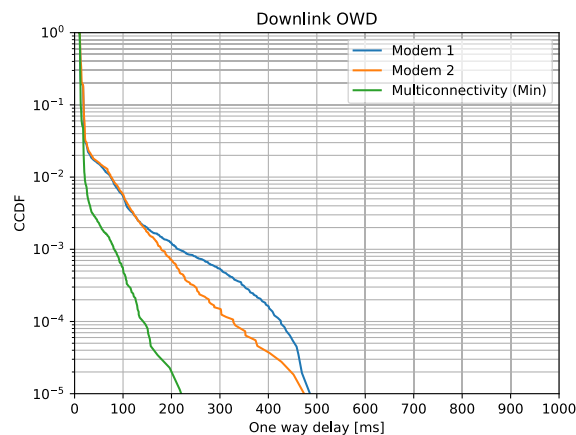


FIGURE 7. Empirical CCDF of DL OWD for modem 1, modem 2 and latency-optimized multi-connectivity.

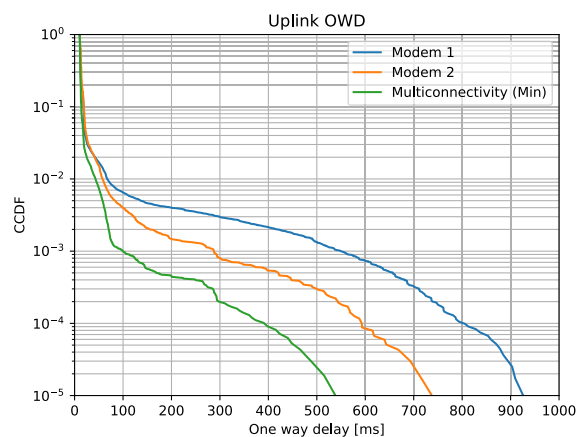


FIGURE 8. Empirical CCDF of UL OWD for modem 1, modem 2 and latency-optimized multi-connectivity.

( $1 - 10^{-5}$ ) level. As displayed, the multi-connectivity scheme based on the selection of the best interface (min) leads to an improved DL OWD, with a median DL OWD of 11.3 ms, and a much more deterministic tail, with contained DL latency lower than 100 ms in 99.9% ( $1 - 10^{-3}$ ) of the cases. With multi-connectivity, at the 99.999% level, the maximum DL OWD was 219.1 ms.

The UL OWD performance results are depicted in Figure 8. UL latency is larger than DL latency due to the fact that in 5G networks, DL transmissions are scheduled almost instantaneously at the base station, while UL communications, initiated by the 5G end device, need to wait for the base station to perform resource allocation and issue an UL grant permission before the data can be transmitted. Both modem 1 and modem 2 exhibited a similar median UL OWD of 11.8 ms and 13.0 ms, respectively, bounded by 100 ms in approximately 99.5% of the cases. The large tails indicated that in 0.1% ( $10^{-3}$ ) of the cases, the UL OWD was larger than 550 ms for modem 1, and 287.4 ms for modem 2. The multi-connectivity gains in UL OWD are smaller than in the DL OWD case. The UL OWD distribution in the multi-connectivity case showed 11.1 ms median value, with a tail

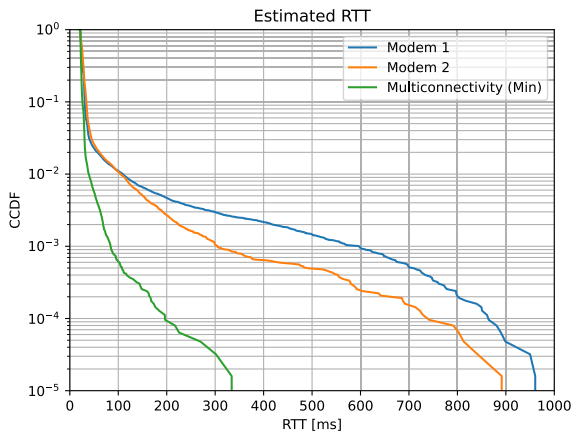


FIGURE 9. Empirical CCDF of the estimated RTT for modem 1, modem 2 and latency-optimized multi-connectivity.

that reaches 100 ms at the 99.9% ( $1 - 10^{-3}$ ) level, and exceeds 0.5 s at the 99.999% level.

Figure 9 shows the estimated RTT latency. As expected, on median level, RTT equals the sum of the median UL OWD and DL OWD contributions, for all the different configurations explored (23.3 ms for modem 1, 25.6 ms for modem 2, and 22.5 ms for the multi-connectivity scheme). As observed, RTT is heavily impacted by the UL performance, exhibiting also a large tail for modem 1 and modem 2, with a RTT latency larger than 100 ms in 1% ( $10^{-2}$ ) of the cases. With multi-connectivity, the tail is reduced, exhibiting a latency lower than 100 ms in only 0.1% of the cases, and bounding the maximum RTT delay to 333.6 ms at the 99.999% level, much lower than that observed individually for modem 1 or modem 2, which were 958.8 ms and 891.5 ms, respectively.

### C. 5G PACKET ERROR RATE

The reliability of the different configurations was also evaluated by means of PER, quantified from the lost packets in the different tests. As detailed in Figure 10, PER was slightly larger in UL than in DL. PER was 0.21% in DL and 0.17% in UL for modem 1. Similar values were observed in modem 2, with a PER of 0.22% in DL and 0.12% in UL. Duplicating the information over the two interfaces of the 5G end user devices has a clear benefit, not only in terms of latency, but also in reliability of information delivery, as the PER can be reduced to values close to zero (0% in DL and 0.02% in UL) by using multi-connectivity. In global terms, PER was better than 1% ( $10^{-2}$ ) for single modem configurations, and better than 0.1% ( $10^{-3}$ ) with multi-connectivity.

### D. 5G DATA RATE PERFORMANCE

The results from the throughput tests are reported in terms of Cumulative Distribution Function (CDF) in Figures 11 and 12, for DL and UL, respectively. It should be noted that the sharp DL throughput cut-off observed for modem 2 in Figure 11 is not a limitation of the 5G network but a measurement device constrain. The modems utilize USB connections that are electrically routed through mini-PCIe

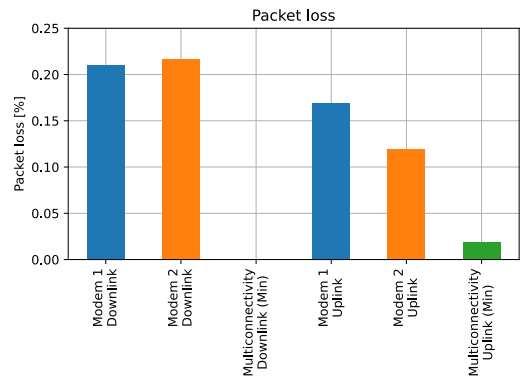
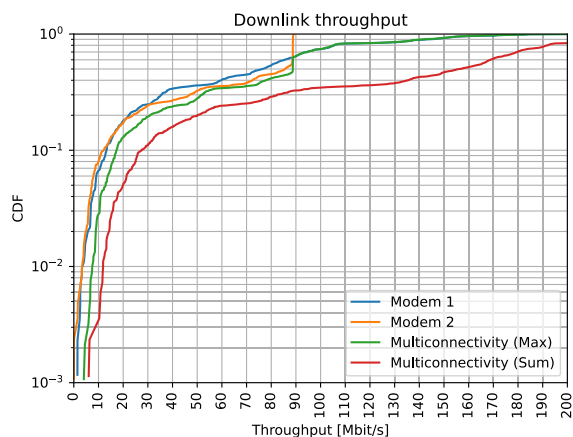


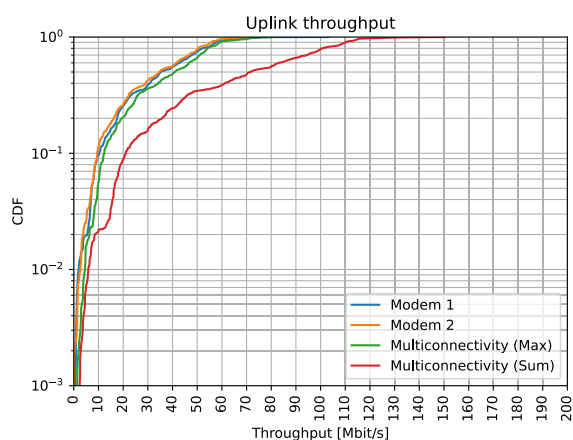
FIGURE 10. PER for modem 1, modem 2 and latency-optimized multi-connectivity.

interfaces to the GW6405 PC. However, the GW6405 has only one mini-PCIe port which is USB 3.0 capable (used by modem 1). The remaining 3 ports, one of which is used by modem 2, are only USB 2.0-capable, which limits the modem to 89 Mbit/s. Therefore, it should be noted that, in practice, the expected DL performance of modem 2 (if unlimited) would be very similar to the one from modem 1, reaching values above 200 Mbit/s. The presented results should still be valid, as the main target of these measurements was to understand what was minimum level of data rates guaranteed/offered by the 5G network. This limitation has a smaller impact the UL data rate performance measurement as, as observed in Figure 12, the throughput values are lower than in DL, and thus closer to the 89 Mbit/s interface limitation of modem 2, leading to a similar distribution experienced by modem 1 and modem 2. However, the maximum UL data rate measured in modem 1 was 102 Mbit/s.

DL throughput was found to be larger than 1 Mbit/s 100% of the time for modem 1, and 99.8% of the time for modem 2. At least 10 Mbit/s were experienced in 95.5% and 93.5% of the cases for modem 1 and modem 2, respectively. 27.8% of the DL throughput samples measured with modem 1 presented values above 100 Mbit/s. As illustrated, the multi-connectivity scheme based on the selection of the best interface (max) leads to a slight improvement in DL throughput as well. This is due to the fact that optimizing latency has, eventually, a beneficial effect on data rates as well, as we are able to transfer data faster. This effect is noticeable mainly in the tails of the distribution, where the low data rates are improved, offering at least 4.1 Mbit/s of minimum DL throughput, instead of the 0-1.5 Mbit/s experienced by individual modems. At median level, this type of multi-connectivity offers 88.7 Mbit/s, showing also some improvement as compared with the individual 75.0 Mbit/s for modem 1 and 85.3 Mbit/s for modem 2. The second multi-connectivity scheme targeting data rate-optimization (sum), leads, as expected, to high gains in throughput based on coordinated exploitation of both interfaces. With this scheme, minimum, median, and maximum DL throughput were improved to 6.0 Mbit/s, 154.8 Mbit/s, and 297.3 Mbit/s, respectively. This performance translates



**FIGURE 11.** Empirical CDF of the DL throughput for modem 1, modem 2, latency-optimized multi-connectivity, and data rate-optimized multi-connectivity.



**FIGURE 12.** Empirical CDF of the UL throughput for modem 1, modem 2, latency-optimized multi-connectivity, and data rate-optimized multi-connectivity.

into 1 Mbit/s in 100% of the cases, 10 Mbit/s in 99.8% of the cases, and 100 Mbit/s in 71.1% of the cases.

UL throughput values are lower than DL throughput values. This was expected, as it depends, not only on the available frequency bandwidth, but also on the TDD UL/DL frame ratio settings in the 5G network. Standard 5G NSA networks are typically configured with a 1/4 or a 3/7 ratio, meaning that data transmissions in DL have between 2.3 and 4 times more resources available for scheduling, which translates into an increase of the effective data rate as compared to the UL. UL throughput was found to be very similar for both modems, with a median value of 35.5 Mbit/s, experiencing 1 Mbit/s and 10 Mbit/s in approximately 99.5% and 91% of the cases, respectively. In terms of multi-connectivity, the scheme based on selection of the best of the two interfaces provides smaller gains in UL as compared to DL (due to the impact of the 5G network access mechanisms explained before). With this type of multi-connectivity, the minimum data rate experienced with modem 1 and modem 2, that was 0-1 Mbit/s, is increased to 1.3 Mbit/s. Median values are

slightly increased to 41.3 Mbit/s, as well as the levels at which 1 Mbit/s and 100 Mbit/s can be guaranteed, which are raised up to 100% and 94.7%, respectively. While no large gains are observed at lower data rates for the multi-connectivity case that makes active simultaneous use of both interfaces (1.8 Mbit/s of minimum throughput), enhances the median data rate to 72.2 Mbit/s and maximum throughput to 150 Mbit/s. This has a positive impact on the levels of specific data rates of interest, where 1 Mbit/s is experienced in 100% of the cases, and 10 Mbit/s and 100 Mbit/s in 97.3% and 22.8% of the cases.

As it may have already been observed, some of the UL throughput test for modem 1 and DL throughput tests for modem 2 reported 0 Mbit/s. The reason for such performance was investigated, finding that those exact tests were performed at those test route areas highlighted in Section IV-A where poor signal conditions or eventual disconnections were experienced.

## V. DISCUSSION

Table 3 summarizes the main QoS test results presented in Section IV for the different configurations: modem 1, modem 2, and the two multi-connectivity schemes for reliability enhancement: the one based on the choice of the best interface out of the two (link/latency-optimized), and the one that makes combined use of the two interfaces (data rate-enhanced). These results are discussed in this Section, where they are put in perspective of the use cases described in Table 1 and their associated communication requirements collected in Table 2, in order to elaborate on the current feasibility of operation of such data-driven agriculture and IoF use cases over 5G. Table 4 outlines the conclusions derived from the discussion.

The trial results indicate that use case 1.1 (machine and data center/server exchange of data, pre- and post-operational) can be operated over early 5G in certain cases. The most restrictive requirement for this use case is the data rate. As link latency is well contained below 100 ms in 99% of the cases, and PER is lower than 1% for all configurations, the service availability is fixed by the UL data rate, which exhibits values higher the required 50 Mbit/s in 65.8% of the cases for single modem configurations and in 81.1% of the cases for the data rate-optimized multi-connectivity scheme. Use case 1.2 (machine and data center exchange of data in real time) has more stringent requirements than use case 1.1 both in terms of latency and data rate, which makes more limited its availability over early 5G. In this case, 100 Mbit/s can only be served in 0.1% of the cases with single modem configurations and in 22.8% of the cases with data-rate optimized multi-connectivity. In order to increase the service availability over 5G of these xMBB use cases related to machine and server data exchange, network density should be improved. Another potential action that could be taken, as these use cases are UL data rate-hungry, is to change the TDD UL/DL frame ratio towards a larger UL value. However, this is not a possibility yet in most 5G NSA

**TABLE 3.** Summary of the 5G IoT performance test results for the different types of evaluated 5G end user types.

5G end user type	Link latency			PER		Effective data rate	
	DL OWD	UL OWD	RTT	DL	UL	DL	UL
Modem 1	min: 9.6 ms med: 11.5 ms max: 486.1 ms 10 ms @0% 50 ms @98.4% 100 ms @99.4%	min: 9.9 ms med: 11.8 ms max: 925.2 ms 10 ms @0% 50 ms @98.2% 100 ms @99.2%	min: 20.8 ms med: 23.3 ms max: 960.7 ms 10 ms @0% 50 ms @97.7% 100 ms @98.9%	0.21%	0.17%	min: 1.5 Mbit/s med: 75 Mbit/s max: 209.3 Mbit/s 1 Mbit/s @100% 10 Mbit/s @95.5% 100 Mbit/s @27.8%	min: 0 Mbit/s med: 35.5 Mbit/s max: 102.2 Mbit/s 1 Mbit/s @99.4% 10 Mbit/s @91.3% 100 Mbit/s @0.1%
Modem 2	min: 9.6 ms med: 12.1 ms max: 473.3 ms 10 ms @0% 50 ms @98.3% 100 ms @99.3%	min: 10.6 ms med: 13.0 ms max: 737.4 ms 10 ms @0% 50 ms @98.5% 100 ms @99.6%	min: 20.9 ms med: 25.6 ms max: 890.6 ms 10 ms @0% 50 ms @97.4% 100 ms @98.9%	0.22%	0.12%	min: 0 Mbit/s med: 85.3 Mbit/s max: 89.2 Mbit/s 1 Mbit/s @99.8% 10 Mbit/s @93.5% 100 Mbit/s @0%(*)	min: 1 Mbit/s med: 35.6 Mbit/s max: 71.6 Mbit/s 1 Mbit/s @99.6% 10 Mbit/s @90.8% 100 Mbit/s @0%(*)
Multi-connectivity (latency-optimized)	min: 9.6 ms med: 11.3 ms max: 219.1 ms 10 ms @0% 50 ms @99.7% 100 ms @99.9%	min: 9.9 ms med: 11.1 ms max: 538.0 ms 10 ms @0% 50 ms @99.2% 100 ms @99.9%	min: 20.6 ms med: 22.5 ms max: 333.4 ms 10 ms @0% 50 ms @99.4% 100 ms @99.9%	0%	0.02%	min: 4.1 Mbit/s med: 88.7 Mbit/s max: 209.3 Mbit/s 1 Mbit/s @100% 10 Mbit/s @97.8% 100 Mbit/s @27.6%	min: 1.3 Mbit/s med: 41.3 Mbit/s max: 81.3 Mbit/s 1 Mbit/s @100% 10 Mbit/s @94.7% 100 Mbit/s @0.1%
Multi-connectivity (data rate-optimized)	min: 9.6 ms med: 12.1 ms max: 708.3 s 10 ms @0% 50 ms @98.3% 100 ms @99.4%	min: 10.6 ms med: 13.0 ms max: 1 s 10 ms @0% 50 ms @98.2% 100 ms @99.2%	min: 20.9 ms med: 25.6 ms max: 1 s 10 ms @0% 50 ms @97.4% 100 ms @98.9%	0.22%	0.17%	min: 6 Mbit/s med: 154.8 Mbit/s max: 297.3 Mbit/s 1 Mbit/s @100% 10 Mbit/s @99.8% 100 Mbit/s @71.1%	min: 1.8 Mbit/s med: 72.2 Mbit/s max: 150.2 Mbit/s 1 Mbit/s @100% 10 Mbit/s @97.3% 100 Mbit/s @22.8%

(\*) Due to specific modem 2 USB 2.0 hardware limitations in the 5G measurement device.

networks at the moment due to spectrum regulations, but it might be in the near future.

Use cases 2.1 (vehicles platooning for joint operation), 2.2 (cooperative safety), 2.3 (extended sensors for cooperative perception), and 2.4 (remote driving and control) are clearly limited by the RTT link latency requirement (10 ms) and the expected PER reliability values, which are lower than 0.1%. The test results indicated that the experienced RTT latency was larger than 20.8 ms for all configurations, and that PER was higher than 0.1% (except for the latency-optimized multi-connectivity scheme), thus, it is safe to report that these use cases are not currently supported in early 5G deployments. These type of mMTC low-latency demanding use cases, will need to wait until future 5G SA Releases (Rel.16 and above) to be serviced over 5G. Within the connected agricultural vehicles use cases, only mMTC use case 2.5 (logistics) can be operated in early 5G deployments. The most restrictive QoS requirement for use case is the DL OWD latency, as the PER requirement of 1% and the 0.5 Mbit/s DL data rates are well supported. Therefore the service availability for use case 2.5 is estimated to be 99.3% for single modem configurations and 99.9% for latency-optimized multi-connectivity schemes. As for the other use cases of this family, 5G SA Rel.16 and above networks will improve further the operational availability.

The family of mMTC use cases dealing with farm machinery direct communication, 3.1 (M2M data exchange and control) and 3.2 (extended machine vision), can be operated partially over early 5G. In both cases, the most limiting QoS factor is the data rate. This sets the service availability of use case 3.1 to 97.8% with single modem configurations and

99.4% with data rate-optimized multi-connectivity. For use case 3.2, as the throughput demand is quite high (100 Mbit/s), its service availability over current 5G will be limited to a 0.1% for single modem configurations and 22.8% when using data rate-optimized multi-connectivity. Potential 5G optimizations for these type of use cases are in line with those stated for use cases 1.1 and 1.2, as the main domain to be upgraded is UL capacity.

The use cases 4.1 (smart device to machine exchange of data) and 4.2 (smart device to machine configuration and diagnostics), belonging to the configuration and diagnostics family, require, to be operated reliably, latencies in the order of 100 ms, PER lower than 1% and data rates of 10 Mbit/s and 1 Mbit/s, respectively. Thus, the early 5G test results indicate that use mMTC case 4.1 can be served in 94.5% of the cases for single modem configurations and 99.9% of the cases for data rate-enhanced multi-connectivity. mMTC use case 4.2 is estimated to have a service availability over early 5G of 98.9% for single modem configurations, and 99.9% for latency-optimized multi-connectivity schemes. As these family of use cases demand a relatively low data rate and present already a good service availability over early 5G, its operability over 5G will automatically improve by network evolution to 5G SA and deployment or Rel.16 and above, potentially reaching service availability levels close to the 99.999%.

It should be noted that, as explained in Section IV-A, in terms of coverage, the explored early 5G deployment provided a coverage level of approximately 96.5%, with distances to the serving 5G cells that were lower than 3 km in 99% of the cases. This guarantees 5G connectivity service

**TABLE 4. Summary of the current 5G capabilities and potential improvements for providing support to the defined IoF use cases.**

IoF class	scenario	Service type	Early 5G service availability	Potential improvements
1.1		xMBB	65.8% for single modem 81.1% with multi-connectivity (data rate-optimized)	5G network densification + + Adjustment of TDD UL/DL ratio
1.2		xMBB	0.1% for single modem 22.8% with multi-connectivity (data rate-optimized)	
2.1		uMTC	Not supported	5G network evolution: SA + Rel.16
2.2		uMTC	Not supported	
2.3		uMTC	Not supported	
2.4		uMTC	Not supported	
2.5		mMTC	99.3% for single modem 99.9% with multi-connectivity (latency-optimized)	
3.1		xMBB	97.7% for single modem 99.4% with multi-connectivity (data rate-optimized)	5G network densification + + Adjustment of TDD UL/DL
3.2		xMBB	0.1% for single modem 22.8% with multi-connectivity (data rate-optimized)	
4.1		xMBB	94.5% for single modem 99.8% with multi-connectivity (data rate-optimized)	5G network evolution: SA + Rel.16
4.2		mMTC	98.9% for single modem 99.9% with multi-connectivity (latency-optimized)	

over the expected communication ranges (50-3000 m) in most of the cases. It is also necessary to highlight, once again, that this study was made on an early 5G deployment. This means that the coverage, performance, and service availability can be expected to improve in the coming years. Still, the reported results exhibit improved network performance as compared to previous published studies. Compared to the latency results reported in [44] for remote supervision of autonomous agricultural machines over a 4G LTE network, early 5G latency is approximately 100 ms better. In term of data rates, the throughput values measured over a 5G NSA network operating in the 3.7 GHz spectrum are approximately 20 Mbit/s higher than those from a pre-commercial 5G network operating in TV White Space (TVWS) spectrum [45]. Altogether, it is already a very positive sign that some of the defined data-drive agriculture and IoF use cases are already feasible up to certain extent as, until now, they were technologically not possible at all.

As stated in the text and in the table, the main 5G network improvements will come linked to the evolution from NSA to SA (eliminating the dependence on the anchor 4G network), and the deployment of 5G Rel.16 and above features, which will enhance xMBB and mMTC applications and will allow to start operating uMTC use cases with ultra-reliability and low-latency QoS requirements. It is expected that Rel.16-capable 5G devices and networks, optimized for industrial agricultural applications, will be commercially available by 2023.

## VI. CONCLUSION

Advanced wireless technologies, such as 5G, offering high reliability, high data rates, and low latency are expected to be an enabler for new applications of digital technology in agriculture. Through this paper, a number of verticals, which have the potential to exploit such new communication technologies to optimize agricultural outputs have been identified. Such vertical lead to the definition of a number of related use case scenarios, together with their associated communication

requirements. Based on the requirements, the use cases were classified according to their service types: Extreme Mobile Broadband (xMBB), Massive Machine-Type Communications (mMTC) and Ultra-reliable Machine-Type Communications (uMTC). An extensive 5G drive test was performed in a representative rural area in the South of Denmark in order to evaluate the suitability of operation for the defined use cases. The trial results, obtained over an early 5G Non Stand-Alone (NSA) Release 15 deployment, revealed median Quality-of-Service (QoS) performance values of 24.5 ms for Round-Trip Time (RTT) link latency, 0.21% for Packet Error Rate (PER) reliability, and 80.1/35.5 Mbit/s for Downlink (DL)/Uplink (UL) data rate, respectively. Such early 5G network performance, indicates that mMTC use cases can be reliably operated in approximately 99% of the cases, while certain xMBB use cases (those requiring data rates up to 10-50 Mbit/s) can be reliably operated in 65.8-97.7% of the cases.

The measurement results suggest that uMTC use cases cannot be supported in early 5G deployments, as they demand extremely low latency (lower than 10 ms), which is not achievable by design over NSA Release 15 configurations. Simple 5G device multi-connectivity schemes, based on the use of two interfaces as opposed to single modem approaches, are proven to enhance the early 5G system performance, and can be of great help for digital agriculture technology integrators. As telecom operators will continue the 5G roll-out and network evolution towards Stand-Alone (SA) and the support Release 16 features, future 5G networks are expected to reliably provide support to all the listed data-driven agriculture use cases for continuing the technological development of the Internet of Farming (IoF).

## REFERENCES

- [1] H. C. J. Godfray, J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin, "Food security: The challenge of feeding 9 billion people," *Science*, vol. 327, no. 5967, pp. 812–818, Dec. 2010. [Online]. Available: <https://science.sciencemag.org/content/327/5967/812>

- [2] M. Bacco, P. Barsocchi, E. Ferro, A. Gotta, and M. Ruggeri, "The digitisation of agriculture: A survey of research activities on smart farming," *Array*, vols. 3–4, Sep. 2019, Art. no. 100009. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2590005619300098>
- [3] A. Tzounis, N. Katsoulas, T. Bartzanas, and C. Kittas, "Internet of Things in agriculture, recent advances and future challenges," *Biosyst. Eng.*, vol. 164, pp. 31–48, Dec. 2017. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1537511017302544>
- [4] J. Stryjak, A. Sharma, B. A. Lucini, and S. Kechiche, "Agricultural machine-to-machine (M2M): A platform for expansion," GSMA Intell., London, U.K., Tech. Rep., 2015. [Online]. Available: <https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2015/03/Agricultural-M2M.pdf>
- [5] S. Wolfert, L. Ge, C. Verdouw, and M.-J. Bogaardt, "Big data in smart farming—A review," *Agricult. Syst.*, vol. 153, pp. 69–80, Apr. 2017. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0308521X16303754>
- [6] S. Monteleone, E. A. D. Moraes, B. Tondato de Faria, P. T. Aquino Junior, R. F. Maia, A. T. Neto, and A. Toscano, "Exploring the adoption of precision agriculture for irrigation in the context of agriculture 4.0: The key role of Internet of Things," *Sensors*, vol. 20, no. 24, p. 7091, Dec. 2020. [Online]. Available: <https://www.mdpi.com/1424-8220/20/24/7091>
- [7] SWAMP Newsletter. (2021). *Precision Irrigation Based on Soil Moisture Awareness Gives 25% Water Saving Potential—Swamp Cartagena Pilot Completed*. [Online]. Available: <http://swamp-project.org/precision-irrigation-based-on-soil-moisture-awareness-gives-25-water-saving-potential-swamp-cartagena-pilot-completed/>
- [8] H. Kim, K. A. Sudduth, and J. W. Hummel, "Soil macronutrient sensing for precision agriculture," *J. Environ. Monitoring*, vol. 11, no. 10, pp. 1810–1824, 2009, doi: [10.1039/B906634A](https://doi.org/10.1039/B906634A).
- [9] N. D. Mueller, J. S. Gerber, M. Johnston, D. K. Ray, N. Ramankutty, and J. A. Foley, "Closing yield gaps through nutrient and water management," *Nature*, vol. 490, no. 7419, pp. 254–257, 2012.
- [10] L. Shi, N. J. H. Marcano, and R. H. Jacobsen, "A survey on multi- unmanned aerial vehicle communications for autonomous inspections," in *Proc. 22nd Euromicro Conf. Digit. Syst. Design (DSD)*, Aug. 2019, pp. 580–587.
- [11] L. Shi, N. J. H. Marcano, and R. H. Jacobsen, "A review on communication protocols for autonomous unmanned aerial vehicles for inspection application," *Microprocessors Microsyst.*, vol. 86, Oct. 2021, Art. no. 104340. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S014193312100497X>
- [12] M. R. Palattella, J. O'Sullivan, D. Pradas, K. McDonnell, I. Rodriguez, and G. Karagiannis, "5G smart connectivity platform for ubiquitous and automated innovative services," in *Proc. IEEE 32nd Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2021, pp. 1582–1588.
- [13] Proagrica. (2022). *Connectivity Within Agricultural Supply Chains*. [Online]. Available: <https://explore.proagrica.com/connectivityagriculture/whitepaper>
- [14] J. H. Jeppesen, E. Ebeid, R. H. Jacobsen, and T. S. Toftegaard, "Open geospatial infrastructure for data management and analytics in interdisciplinary research," *Comput. Electron. Agricult.*, vol. 145, pp. 130–141, Feb. 2018. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168169917308293>
- [15] W. Tao, L. Zhao, G. Wang, and R. Liang, "Review of the Internet of Things communication technologies in smart agriculture and challenges," *Comput. Electron. Agricult.*, vol. 189, Oct. 2021, Art. no. 106352. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168169921003690>
- [16] Y. Tang, S. Dananjayan, C. Hou, Q. Guo, S. Luo, and Y. He, "A survey on the 5G network and its impact on agriculture: Challenges and opportunities," *Comput. Electron. Agricult.*, vol. 180, Jan. 2021, Art. no. 105895. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168169920331008>
- [17] E. Hecker, D3.2. *The IoT2020 Use Case Architectures and Overview of the Related IoT Systems—Task T3.1. Smart Agri-Food Solution Reference Architecture and Interoperability Endpoints Specification*, Schuttelaar Partners, Brussels, Belgium, 2020.
- [18] IoT2020. (2021). *Internet of Food and Farm*. [Online]. Available: <https://www.iof2020.eu/>
- [19] P. Popovski, K. F. Trillingsgaard, O. Simeone, and G. Durisi, "5G wireless network slicing for eMBB, URLLC, and mMTC: A communication-theoretic view," *IEEE Access*, vol. 6, pp. 55765–55779, 2018.
- [20] C. Sørensen, S. Fountas, E. Nash, L. Pesonen, D. Bochtis, S. Pedersen, B. Basso, and S. Blackmore, "Conceptual model of a future farm management information system," *Comput. Electron. Agricult.*, vol. 72, no. 1, pp. 37–47, 2010. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168169910000396>
- [21] C. Brewster, I. Roussaki, N. Kalatzis, K. Doolin, and K. Ellis, "IoT in agriculture: Designing a Europe-wide large-scale pilot," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 26–33, Sep. 2017.
- [22] M. Lauridsen, I. Z. Kovacs, P. Mogensen, M. Sorensen, and S. Holst, "Coverage and capacity analysis of LTE-M and NB-IoT in a rural area," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2016, pp. 1–5.
- [23] B. Vejlggaard, M. Lauridsen, H. Nguyen, I. Z. Kovacs, P. Mogensen, and M. Sorensen, "Coverage and capacity analysis of sigfox, LoRa, GPRS, and NB-IoT," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–5.
- [24] O. JiHye, D.-H. Noh, and Y.-H. Sohn, "Empirical test of Wi-Fi environment stability for smart farm platform," in *Proc. 4th Int. Conf. Comput. Appl. Inf. Process. Technol. (CAIPT)*, Aug. 2017, pp. 1–5.
- [25] S. Frattasi, H. Fathi, F. H. P. Fitzek, R. Prasad, and M. D. Katz, "Defining 4G technology from the users perspective," *IEEE Netw.*, vol. 20, no. 1, pp. 35–41, Jan. 2006.
- [26] A. Barreto, B. Faria, E. Almeida, I. Rodriguez, M. Lauridsen, R. Amorim, and R. Vieira, "5G—Wireless communications for 2020," *J. Commun. Inf. Syst.*, vol. 31, no. 1, Jun. 2016.
- [27] A. Fornes-Leal, R. Gonzalez-Usach, C. E. Palau, M. Esteve, D. Lioprasitis, A. Priovolos, G. Gardikis, S. Pantazis, S. Costicoglou, A. Perentos, E. Hadjiioannou, M. Georgiades, and A. Phinikarides, "Deployment of 5G experiments on underserved areas using the Open5GENESIS suite," in *Proc. Int. Conf. Smart Appl., Commun. Netw. (SmartNets)*, Sep. 2021, pp. 1–4.
- [28] M.-A. Kourtis, T. Anagnostopoulos, S. Kukliński, M. Wierzbicki, A. Oikonomakis, G. Xilouris, I. P. Chochliouros, N. Yi, A. Kostopoulos, L. Tomaszewski, T. Sarlas, and H. Koumaras, "5G network slicing enabling edge services," in *Proc. IEEE Conf. Netw. Function Virtualization Softw. Defined Netw. (NFV-SDN)*, May 2020, pp. 155–160.
- [29] A. Rostami, "Private 5G networks for vertical industries: Deployment and operation models," in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Sep. 2019, pp. 433–439.
- [30] H. Holma, A. Toskala, and T. Nakamura, *5G Technology: 3GPP New Radio*. Hoboken, NJ, USA: Wiley, 2020.
- [31] B. Bertenyi, "5G evolution: What's next?" *IEEE Wireless Commun.*, vol. 28, no. 1, pp. 4–8, Feb. 2021.
- [32] G. Liu, Y. Huang, Z. Chen, L. Liu, Q. Wang, and N. Li, "5G deployment: Standalone vs. non-standalone from the operator perspective," *IEEE Commun. Mag.*, vol. 58, no. 11, pp. 83–89, Nov. 2020.
- [33] G. Pocovi, T. Kolding, M. Lauridsen, R. Mogensen, C. Markmiller, and R. Jess-Williams, "Measurement framework for assessing reliable real-time capabilities of wireless networks," *IEEE Commun. Mag.*, vol. 56, no. 12, pp. 156–163, Dec. 2018.
- [34] I. Rodriguez, R. S. Mogensen, A. Fink, T. Raunholt, S. Markussen, P. H. Christensen, G. Berardinelli, P. Mogensen, C. Schou, and O. Madsen, "An experimental framework for 5G wireless system integration into industry 4.0 applications," *Energies*, vol. 14, no. 15, p. 4444, Jul. 2021, doi: [10.3390/en14154444](https://doi.org/10.3390/en14154444).
- [35] Goodmill Systems. (2022). *W24H-I Managed Multichannel Router, Data Sheet*. [Online]. Available: [https://goodmillsystems.com/application/files/6415/8918/4750/Goodmill\\_w24h-I\\_Datasheet.pdf](https://goodmillsystems.com/application/files/6415/8918/4750/Goodmill_w24h-I_Datasheet.pdf)
- [36] TDC Erhverv 5G | Fremtidens Teknologi—TDC Erhverv. Accessed: Dec. 7, 2021. [Online]. Available: <https://tdc.dk/5g>
- [37] 5G—Fremtidens Netværk Åbner Din Verden. Accessed: Dec. 7, 2021. [Online]. Available: <https://www.telenor.dk/shop/landingpage/5g/>
- [38] John Deere 6R 155 Tractor. Accessed: Feb. 23, 2022. [Online]. Available: <https://www.deere.com/en/tractors/row-crop-tractors/row-crop-6-family/6155r-tractor/>
- [39] Gateworks Newport GW6400 Single Board Computer. Accessed: Feb. 9, 2022. [Online]. Available: <https://www.gateworks.com/products/industrial-single-board-computers/octeon-tx-single-board-computers-gateworks-newport/gw6400-single-board-computer/>
- [40] L. D. Vito, S. Rapuano, and L. Tomaciello, "One-way delay measurement: State of the art," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 12, pp. 2742–2750, Dec. 2008.
- [41] Simcom SIM8300g-m2. Accessed: Feb. 10, 2022. [Online]. Available: [https://www.simcom.com/product/SIM8300G\\_M2.html](https://www.simcom.com/product/SIM8300G_M2.html)

- [42] *Gateworks GW16140 M.2 to Mini-PCIe Adapter Card*. Accessed: Feb. 10, 2022. [Online]. Available: <https://www.gateworks.com/products/mini-pcie-expansion-cards/gw1614x-mini-pcie-to-m2-adapter-card/>
- [43] *IPERF—The Ultimate Speed Test Tool for TCP, UDP and SCTP*. Accessed: Feb. 10, 2022. [Online]. Available: <https://iperf.fr/>
- [44] M. Green, D. D. Mann, and E. Hossain, “Measurement of latency during real-time wireless video transmission for remote supervision of autonomous agricultural machines,” *Comput. Electron. Agricult.*, vol. 190, Nov. 2021, Art. no. 106475.
- [45] M. Razaak, H. Kerdegari, E. Davies, R. Abozariba, M. Broadbent, V. Argyriou, and P. Remagnino, “An integrated precision farming application based on 5G, UAV and deep learning technologies,” in *Computer Analysis of Images and Patterns* (Communications in Computer and Information Science), M. Vento, G. Percannella, S. Colantonio, D. Giorgi, B. Matuszewski, H. Kerdegari, and M. Razaak, Eds. Berlin, Germany: Springer-Verlag, Sep. 2019, pp. 109–119.



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