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Converging Telco-Grade Solutions 5G and beyond to Support Production in Industry 4.0

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Abstract: The Industry 4.0 initiative has been showing the way for industrial production to optimize operations based on collecting, processing, and sharing data. There are new requirements on the production floor: flexible but ultra-reliable, low latency wireless communications through interoperable systems can share data. Further challenges of data sharing and storage arise when diverse systems come into play at the Manufacturing Operations Management and Business Planning & Logistics levels. The emerging complex cyber-physical systems of systems need to be engineered with care. Regarding industrial requirements, the telecommunication industry has many similarities to production—including ultra-reliability, high complexity, and having humans "in-the-loop". The current paper aims to provide an overview of converging telco-grade solutions that can be successfully applied in the wide sense of industrial production. These toolsets range from model-driven engineering through system interoperability frameworks, 5G- and 6G-supported manufacturing, and the telco-cloud to speech recognition in noisy environments.

Keywords: 5G; 6G; industry 4.0; industrial IoT; MES; ERP; manufacturing; model-driven engineering; telco cloud; speech recognition; reliability

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1. Introduction

While the requirements of the Industry 4.0 initiative has conceived in the industrial production domain, many of its solutions and approaches arrive from ICT (Information and Communication Technology). This is due to the fact that the main enablers of this revolution are engineering and business data collection, processing, and sharing. Nevertheless, industrial production has its well-established set of standard requirements on safety, security, reliability, and its naturally high complexity that is broken down to functional modules, which build the processes themselves. The new and the traditional requirements seem hard to be satisfied together—as an example, systems communicating while being mobile have been hard to imagine on the manufacturing floor where reliable real-time communication is a key to production quality.

Similar to industrial production, the telecommunications sector values high-reliability [1], security [2], as well as detailed system planning [3] and modeling [4], traditionally. It is well-known that many of the paradigms applied by the Industry 4.0 movement have originated from IT (Information Technology)—and it is partially the cause why industrial practitioners are unwilling to adopt them. Mostly due to the complexity of the implemented system of systems and the cost of unplanned downtime, production engineers share the idea of "never-touch-a-running-system" with telco practitioners. In the telco industry, network freeze (i.e., no new updates or changes) is introduced in high revenue-generating periods: usually starting in early December and lasting for a month, so the highly-utilized Christmas festive period runs smoothly. In contrast, industrial production runs in "highly critical mode" most of the time, and any change or update that affects service guarantees are only allowed to be executed within well-planned, predefined maintenance windows. Industry practitioners, however, are willing to embrace ICT technologies as long as they are highly tested, proven, and their complexity is broken down, so the system of systems they operate is still explainable.

Besides their application of similar approaches towards complex systems—such as model-driven engineering—, the telecommunications and industrial production sectors now endorse wireless ultra-reliable low latency communications (URLLC) and mass IoT together. The industry-motivated URLLC scenarios are covered by 5G that is provided by the telecommunications sector together with the two other main application areas, massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB) [5]. Moreover, the telco-cloud concept further ensures ultra-reliability, low latency, highly dynamic service flexibility, and high security, making sure that end-to-end slicing service guarantees are met. The 6G standardization has just been started, and the requirement-setting is still in an expanding phase. Just to mention a few of the promises, 6G aims to allow ultra-high density of endpoints communication even with terabit per second throughput, tactile internet with real AR/VR capabilities, and ubiquitous connection and services that are available anywhere, anytime.

Ergonomic human–machine interfaces continue to be highly important in modern life—including human–robot co-working environments. The most natural command interface for humans is speech itself; hence speech-controlled environments are important alternatives to character—or gesture-based ones in industrial production. The basis of speech-controlled human–machine interfaces is speech recognition itself, a core problem and solution set of telecommunications for decades.

The current paper aims to provide an overview of these above-listed approaches and technologies—conceived at least partially in the telecommunications sector—being applied in industrial production.

The contributions of this paper are the following:

- It compiles a state-of-the-art survey on how 5G-related technologies and the requirements set for 6G affect the Industry 4.0 movement;
- It provides a comprehensive overview on model-driven engineering (MDE) techniques and tools to be used for planning, modeling, and designing complex systems;
- It outlines interoperability and integrability frameworks for cyber-physical system of systems to be applied in multi-level, multi-stakeholder industrial production;
- It extends the 5G service slicing guarantees with the offerings of telco-clouds;
- It provides an overview of speech recognition applications in the production area, including security-related issues and handling noisy environments.

The rest of the paper is organized as follows. Section 2 describes the ecosystem of industrial production in broad and narrow senses, including the stakeholders and their interoperability. Section 3 provides a comprehensive overview and comparison of modeling approaches and frameworks in the field of Industrial IoT. Regarding operational production systems, Section 4 surveys how information flow is made smoother when 5G and 6G technologies are on board – and it is extended by an analysis of telco cloud possibilities in Section 5. Human–machine communication can be made more natural (for humans) by the use of speech commands – their usage in the industrial sector is surveyed by Section 6. Section 7 concludes the paper. For better visibility, the structure of the paper is illustrated by Figure 1.

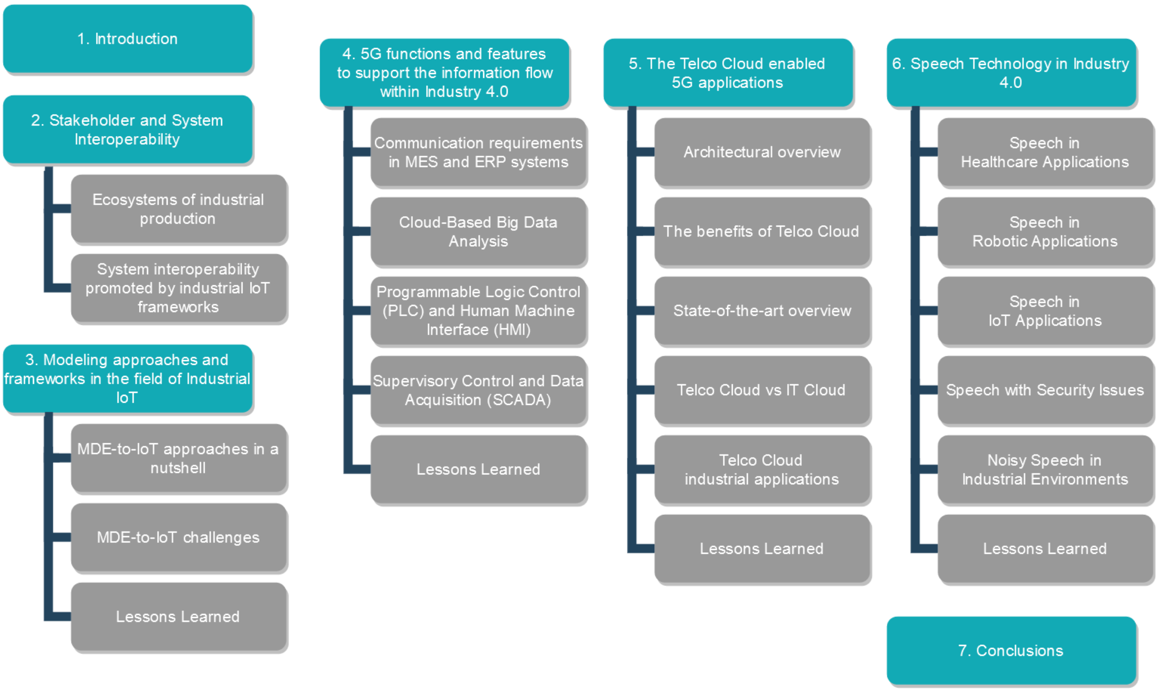

Figure 1. Structure of the current paper.

2. Stakeholder and System Interoperability

2.1. Ecosystems of Industrial Production

Industry 4.0 is often envisioned so that the methods and tools that are associated with IT (Information Technology) and OT (Operational Technology) are converging [6]—although this is a simplification. Information sharing across all levels is a critical key principle—hence ICT is a better term to cite—as well as real-time feedback, security, and high reliability (which are related requirements).

The importance of information sharing throughout the ecosystem cannot be overestimated—neither the challenges it implies for Industry 4.0. One way to demonstrate stakeholder heterogeneity is through the logistics and supply chain approach of Figure 2. Data on individual assets, their feature description, status, location or even lifecycle history are available to get shared securely throughout the value chain. The same applies to the data related to the production or logistics processes as well.

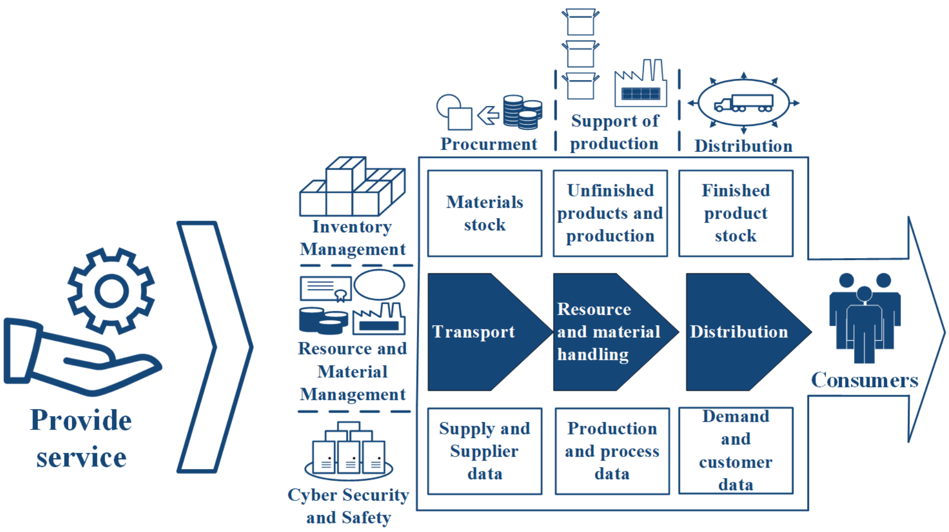

Figure 2. Main stakeholders and processes of a generic supply chain [7].

When narrowing down the ecosystem to the production itself—which happens in the manufacturing plant—the stakeholders are traditionally the production equipment vendors, the providers of "raw" or pre-processed materials, the production owner itself, and the distributors. In production with advanced Industry 4.0 capabilities, however, the communications (equipment or service) provider comes to play as well. This is because the deployment and operation of flexible but reliable and secure communication systems require a special skill set and experience that is found best in the resume of ICT engineers.

The Industry 4.0 ecosystem aims to provide more flexible, cheaper, environment-friendly, and sustainable factories. To investigate and evaluate this ecosystem only from the Industrial Production perspective the focus shall be on production floor elements. The key members' responsibility in this environment is presented—as shown in Figure 3—and briefly introduced the connections between them.

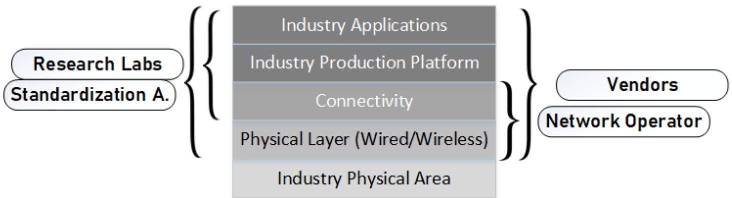

Figure 3. The Industry ecosystem's members.

2.1.1. Key Stakeholders

The participants, as shown in Figure 3, define the main directions and invest the most in developing the actual communication technologies. Firstly, the **Standardization Agencies** as 3GPP, ITU, IETF and IEEE, etc., are responsible for recommending and defining the communication standards. They also describe methodologies and create models on how to interconnect different systems. Their global presence and historical background qualify them to work globally, while HW and SW **Vendors** can use the published standards as the base for their development and maintenance processes. **Network Operator (NO)**—be it public or private—is a crucial participant as they provide the data connectivity for the production platforms. To fulfill this, they need to provide physical connection either as wired cabling or wireless connectivity systems, including licensed and non-licensed solutions. NOs use the existing standardized solutions and devices made by the Vendors to provide scalable services and cover a broad spectrum. Vendors are developing and manufacturing devices and network solutions based on the standards, but their products can differ significantly, leading to interoperability issues. Due to the limited Vendors and possible interoperability problems, the initial Vendor selection by NOs is crucial for further network development. **Research laboratories** are also fundamental players in this ecosystem as they can both bring the new ideas and materialize them and be the catalyzers between the standard and the implementation at NOs and Vendors. Research Lab developments are generally the playground for Vendors and NOs before investing in public rollout with strict service and quality requirements.

2.1.2. Comparison of Industrial and Residential 5G

There is a significant difference between mobile network services provided for public or industrial purposes. Although both are based on existing 3GPP standards, the use-case and user requirements are fundamentally different; therefore, the architectural solutions will be diversified [8]. The comparison is summarized in Table 1.

The **subscriber** in the case of the existing mobile networks is mainly the human population, and to a lesser extent IoT devices. They utilize mobile services in a relatively large area. In contrast, Industry 4.0 users will be mostly machines, operating in a well-defined geographical area.

Table 1. Comparison of a few factors of Residential and Industrial 5G from NOs' perspective.

	Residential	**Industrial**
Subscriber	Mainly human	Mainly machine
Subscription	Monthly/pre-paid	Yearly with more years of contract
Services	Wide range, fast changing	Permanent, not expected to change
SIM fluctuation	High	None, until services exits
Reliability	High; however, no guarantee	High with guarantee
Troubleshooting	Not critical	Critical with contract to Service Level Agreements
SLA	Not compulsory	High

The nature of **subscription** is also different. Traditional mobile network subscribers pay every month based on subscription type or data usage. Thus, service pricing can be fine-tuned based on network resource utilization per user basis. In the case of industrial solutions, it is expected that the entire industrial solution will pay a service fee for the service. Regardless of the devices' data or resource utilization, or which use-case has a temporary high demand, pricing is not followed by a direct financial change. Industrial subscription fees will be much simpler and more stable than traditional public network pricing.

The number of available **mobile network services** will be much more limited for industrial solutions. Machine Type of Communication is unlikely to need a voice, SMS/MMS, and roaming service in addition to a data connection. On the other hand, an industrial service must be operational throughout the life cycle of the factory. The fluctuation of services based on existing essential services, such as OTT (Over-The-Top), is also expected to be low for industrial mobile networks. However, the high reliability and stability of existing ones are vital.

SIM fluctuation and user churn will be close to zero for industrial services, or at least it will not be typically seasonal. A machine connected to an industrial 5G network solution is expected to use one SIM card throughout its life cycle.

In terms of **reliability**, industrial networks must perform well above the requirements of existing public mobile networks and services. **Troubleshooting** time commitments should also be adjusted to industrial needs. The transmission of data or voice packets in the current public mobile networks works on a best-effort basis, so there is no guarantee for the services based on them. In the case of a public user complaint, the user cannot enforce any obligation on the NO. In contrast, it is inevitable to make commitments and define **Service Level Agreements (SLAs)** regarding the required services on the factory site. SLAs can include several metrics depending on the use-case requirements; the most fundamental ones are the bandwidth, latency, and availability.

2.2. System Interoperability Promoted by Industrial IoT Frameworks

The potentials of the Internet of Things (IoT) concept has become clear for the production industry as well, although there were clear obstacles to be handled. These include the issues with security, real-time operation, engineering complexity, interoperability, and the integrability of legacy equipment. Beside the numerous individual approaches, several collaborations created toolsets and frameworks to satisfy the needs of industrial IoT ecosystems. The following paragraphs provide a brief overview of the frameworks with the most current interest. A more comprehensive survey is provided by Ref. [9].

LWM2M stands for Lightweight Machine to Machine communications, proposed by the OMA SpecWorks [10]. As its name suggests, LWM2M aims for providing the means for M2M communications. Its main purpose is to allow low-power devices to become integrated into IoT infrastructures through the REST-based Constrained Application protocol, CoAP.

IoTivity is an open-source platform originally developed for smart-home applications, then broadened to address emerging IoT requisits through ensuring device-to-device connectivity. It is promoted by the Open Connectivity Foundation (OCF), which has other interesting initiatives, including the OCF framework itself [11], that addresses interoperability issues for all sorts of devices so they can be integrated into networks. Another reference model of the OCF Foundation is called Industrial Data Space (IDS) [12], implementing three major core concepts (security, certification, and governance) across a five-layer structure (system, information, process, functional, and business) —hence aiming for system-wide interoperability.

AUTOSAR targets the automotive industry, as it provides standards for electronic control units (ECU) through a layered software framework for intelligent mobility [13].

BaSys has started as a research project for "Basic system Industry 4.0", and it has evolved into the Eclipse BaSyx project. It provides components to implement Industry 4.0 applications including production digitalization, connectivity between production floor and IT, changeable production processes, and many more—although it does not support time critical applications with run-time operation control [14].

The FIWARE platform manages contextual information and provides a set of standards for their handling—which distinguishes it from other frameworks. It supports various application areas such as smart cities, production plants, or smart energy grids [15].

The ultimate aim of the Arrowhead framework is to achieve interoperability between heterogeneous systems in a secure way, using existing protocols, standards, and to allow integration of legacy systems [16]. Distinguishing features of the Arrowhead framework includes the adoption of Service-Oriented Architecture principles, and the definition of local automation clouds [17] that assists real-time operation, increased security [18] and reduces engineering complexity. The systems and services of Arrowhead are now federated as an open source Eclipse project [19].

The key principles of Service-Oriented Architectures (Lookup, Late Binding, Loose Coupling) allows Arrowhead-compatible systems to dynamically connect, produce and consume services to/from each other (i.e., exchange information). When becoming available (i.e., after wake-up or getting their resources freed), service producing systems get in contact with the Arrowhead Service Registry core system, which records the service availability. On the other hand, when a system requires to consume a given service (e.g., reading vibration or stream processing a data-set), it contacts the Arrowhead Orchestrator and the Authorizer core systems, so it receives access to a service producer. After this match-making procedure, systems communicate with the protocol of their preference, hence real-time operation is not disturbed by the capabilities of the Arrowhead core [20]. System compatibility issues have to be clarified during the orchestration phase, or handled through translators that Arrowhead can also provide [21].

Arrowhead also promotes ecosystem-wide interoperability [7,22]. Local automation clouds defined on the production floor can have inter-cloud connections to data processing systems and Manufacturing Execution Systems (MES) on the Manufacturing Operations Management level, as well as to Enterprise Resource Planning (ERP) systems on the Business Planning and Logistics level. This approach for secure information exchange between loosely coupled systems can be extended inter-enterprise, throughout whole ecosystems and supply chains [23], as Figure 4 suggests.

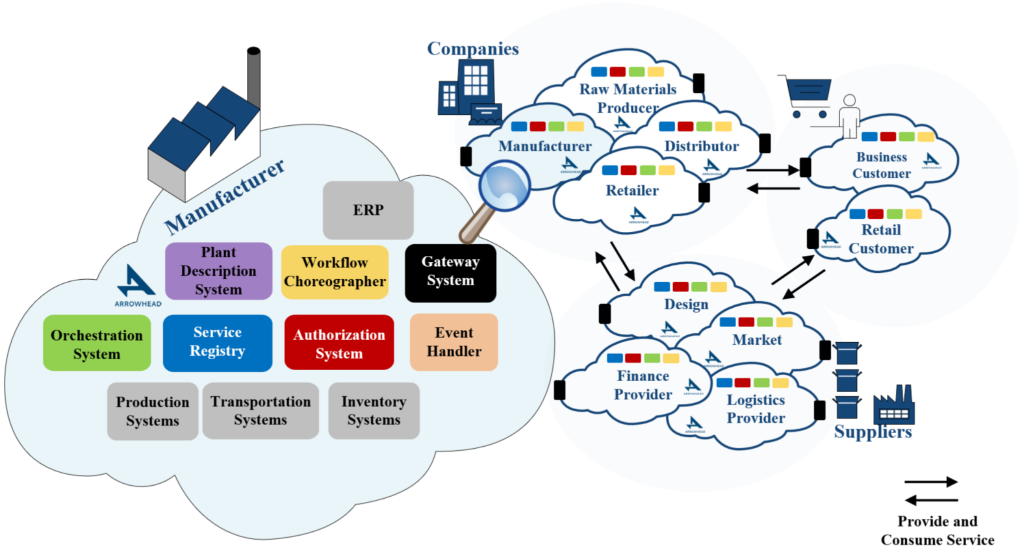

Figure 4. Extended supply chain management with the Arrowhead framework [7].

Following this thread, the telco-grade solutions described in the current paper can also be part of the System of Systems formed within industrial production ecosystems. A high-level representation of this approach is shown by Figure 4.

3. Modeling Approaches and Frameworks in the Field of Industrial IoT

Modeling represents the core concept in Model-Driven Engineering (MDE) and is considered an abstraction of the system under development. A modeling language definition describes the set of available concepts and well-formed rules to which a valid model must conform. A meta-model describes the set of available concepts and well-formed rules to which a valid model must conform. The heterogeneity of software and hardware is a major challenge in the world of IoT [24]. MDE can provide a unique means for the many aspects of heterogeneous systems to be represented all in one place thanks to modeling languages, specifically domain-specific ones (DSLs) [25]. Models defined by these languages are intended to be far more human-oriented than common code artifacts, which are inherently machine-oriented. This means that concepts such as software can be defined without regard to the underlying platform or technology.

Over the last decade, there has been a growing demand for model-based solutions to address specific IoT challenges ranging from heterogeneous application development and management to real-time models and system monitoring. In this chapter, we will provide a brief overview of the various modeling approaches and frameworks used in industrial IoT, as well as their comparison and evaluation. This is, to the best of our knowledge, the first survey paper that provides a comprehensive overview of—and comparison of—modeling approaches and frameworks in the field of Industrial IoT. We contribute by identifying the main challenges in this field and comparing fully-fledged modeling frameworks based on the identified challenges and their solutions.

3.1. MDE-to-IoT Approaches in a Nutshell

We conducted a literature review to better understand the relationship between MDE and IoT. We have gathered a number of MDE approaches that can aid in the development of IoT applications. In this section, we will provide a high-level overview of these MDE-to-IoT approaches. We divided the approaches into two categories: (i) Full-fledged MDE tools and IoT frameworks (ii) IoT general MDE mechanisms (for example, UML profiles [26]).

3.1.1. Fully-Fledged MDE Tools and Frameworks for IoT

Papyrus

Papyrus for IoT [27] is an Eclipse-based framework for managing heterogeneous IoT applications, development environments, devices, and communication technologies. Papyrus supports real-time models, which allow for run-time manipulation of the system's behavior in response to changes in the IoT system.

IEC61499 Standard

The IoT industry is shifting away from centralized systems and toward a more distributed paradigm. Large systems with a centralized intelligence in charge of everything are being transformed into distributed systems. Individual parts in a distributed system have intelligence and can communicate with one another smoothly, so the system functions as a whole. The IEC61499 standard [28] defines function blocks that can be used to develop distributed control applications, as well as how these are interpreted and executed. Its functionality and dynamic reconfiguration support provide the necessary infrastructure for Industry 4.0 and industrial IoT applications. Many implementations [29] of the IEC61499 standard have appeared in the literature over the last decade. Eclipse 4diac [30] is one of the most influential IEC61499 tools. In the following sections, we will look at Eclipse 4diac as the primary representative of IEC61499. Based on the IEC61499 standard, Eclipse 4diac is an open source framework for distributed industrial process measurement and control systems. For users, Eclipse 4diac provides an IEC61499 compliant development environment, a runtime environment, and a function block library.

Eclipse Vorto

Eclipse Vorto [31] provides an easy-to-use domain-specific language for describing IoT device capabilities. As an Information Model, this language can be used to describe the functionality of an IoT device. Vorto also offers the Vorto Repository, which is an open platform for sharing and managing device descriptions.

FRASAD

FRASAD (Framework for Sensor Application Development), a model-driven approach for improving the reusability and flexibility of sensor software systems, has been proposed in [32]. The system is described using a rule-based model and a Domain Specific Language (DSL) in this approach. The FRASAD tool includes a graphical user interface, code generation components, and supporting tools to assist developers in modeling, implementing, and testing an IoT system.

ThingML

ThingML [33,34] is a framework that includes a modeling language, a set of tools, and a methodology. The language of ThingML combines well-proven UML-aligned software-modeling constructs (statecharts and components), an imperative platform-independent action language, and IoT-specific constructs. ThingML has several industrial applications, including [35,36].

IoTA-MD

IoTA-MD [37] is a modeling tool that helps with the design and maintenance of complex IoT systems. IoTA-MD addresses IoT system development complexity issues from both vertical and horizontal perspectives. Handling quality attributes separately from the domain and information models addresses the horizontal issue. The vertical issue is addressed by designing system models with the appropriate abstraction level using Model-Driven Architecture (MDA) [38].

AutoIoT

AutoIoT [39] is a framework for developing IoT applications that is based on a user-driven MDE approach. AutoIoT allows users to model their IoT systems using a JSON description and then generates a ready-to-use IoT server-side application using internal model-to-model and model-to-text transformations.

MagicDraw

MagicDraw [40] is a popular modeling tool for business process, software, and system modeling. Several MDE approaches in the literature are based on the MagicDraw ecosystem. In [41], the authors introduce an abstract SysML profile for the Arrowhead System of Systems (SoS) design, which is implemented as a MagicDraw plugin, focusing on the relationship between MDE and IoT. The plugin allows you to create high-level functional models of the specific Arrowhead SoS application and then import them into the Arrowhead Management Tool.

3.1.2. General MDE Mechanisms for IoT

Aside from the fully-fledged MDE tools and frameworks mentioned above, there are emerging general MDE mechanisms for IoT in the literature. UML [42] and SysML [43] are widely regarded as de facto standards for software and systems development, respectively. Both UML and SysML have IoT extensions. UML4IoT [44,45] is a UML profile [26], which is a specialization of the UML's meta-model with IoT-specific constructs.

SysML4IoT [46] is a SysML profile adaptation that addresses the heterogeneity of hardware devices and software components in IoT system modeling. SysML4IoT includes abstractions for describing various types of hardware devices and software services. Another abstract SysML profile for Arrowhead System of Sytems (SoS) design is proposed in [41]. This SysML profile is intended to create abstract Arrowhead SoS instances.

3.2. MDE-to-IoT Challenges

We describe how the MDE-to-IoT approaches address the identified challenges in this section. We compare and evaluate fully-fledged MDE tools and frameworks such as Papyrus for IoT, Eclipse 4diac, Eclipse Vorto, FRASAD, ThingML, IoTA-MD, AutoIoT, and the MagicDraw-based approach. During our review of the literature, we identified three challenges related to model-driven engineering and IoT: (i) Handling heterogeneity through abstraction; (ii) code generation for heterogeneous platforms; (iii) real-time models for monitoring and supervising running IoT systems.

3.2.1. Handling Heterogeneity through Abstraction

The alpha and omega of any kind of system modeling, including the modeling of complex IoT systems, is conquering complexity by selecting the appropriate level of abstraction for the problem domain being analyzed. IoT is one of the most rapidly growing areas of the industrial technology. However, the way IoT is evolving raises serious concerns: there are far too many complexities, moving parts, diversities, and competing trends and technologies to consider when developing IoT solutions. One practical approach to dealing with the complexities of IoT would be to use the concept of *abstraction* to create solutions that can deal with issues and diversities at different levels while remaining flexible in the face of constant changes. Through the activity of *modeling*, abstraction can help with the specification and design of complex IoT systems. The chosen tools and approaches provide various modeling facilities to aid in the specification and design of complex IoT systems. In this section, we summarize and evaluate the modeling languages that the various tools support for dealing with heterogeneity.

In Papyrus, system requirements can be specified using UML use case diagrams [42] and SysML requirements diagrams [47]. The IoT system's use cases can be formally described and derived from the purpose and requirements specification. After defining the requirements, the functional architecture of the system can be defined using the IoT domain model, which is provided as an extension of MARTE [48] and SysML. Aside from defining the functional architecture of the system, the operational platform on which the functional system will be executed must also be defined. The system's operational view includes information about computing devices, sensors, actuators, and communication protocols. Finally, using the Papyrus Designer Component, one must define deployment plans that include information on the allocation of functional blocks to operational ones. Finally, Papyrus provides modeling solutions that can deal with issues and diversity at various levels: it allows you to specify, design, and deploy IoT systems.

The Eclipse 4diac platform is based on the IEC61499 standard, which defines a domain-specific modeling language for developing distributed industrial control solutions in IoT. The IEC61499 standard includes several languages that can be used to program higher-level industrial control applications. The main components of the IEC61499 standard are: (i) Graphical language for programmable logic controller design that can describe the function between input variables and output variables, (ii) Graphical Execution Control Chart (ECC) of basic functional blocks that determines the algorithm to execute based on the current input event and data variables, and (iii) Structured Text (ST), which can be used to describe the function blocks' algorithms. Remember that the scope of Eclipse 4diac differs from that of Papyrus. While Papyrus provides an abstraction for specifying, designing, and deploying IoT systems, the modeling languages implemented in Eclipse 4diac target a narrower domain, only facilitating the development of distributed control solutions in industrial IoT.

For the creation of Information Models, Eclipse Vorto provides two options: (i) Graphical DSL (based on Eclipse Sirius [49]) aimed at business users with no or little programming experience and (ii) Textual DSL (based on Eclipse Xtext [50]) aimed at developers with an IT background. The information models in both languages are built from reusable, abstract, and technology-agnostic Function Blocks.

The IoT system is described in FRASAD using a rule-based model and a textual DSL, allowing system designers to describe their IoT application using only sensor network domain concepts. The DSL aims to decouple programming languages and their execution models from the underlying operating system and hardware. FRASAD's scope is narrower than Papyrus': the modeling facilities provided by FRASAD are intended to facilitate only sensor application development at a higher level of abstraction.

ThingML provides three key abstraction pillars: architecture models, statecharts, and ThingML's action language. Components, ports, connectors, and asynchronous messages comprise the architecture model. Once the general architecture is defined, ThingML allows for the platform-independent specification of the components' business logic using statecharts and the ThingML action language.

IoTA-MD offers four different types of models that can be used in the IoT development process: (i) a domain model to describe the abstract representation of the concepts, responsibilities, and relations required by IoT stakeholders; (ii) an information model to describe all Domain model concepts that are explicitly represented in the digital world, as well as the relationships between them; (iii) a perspective model that enables the handling of non-functional requirements (quality attributes) during application domain design; and (iv) a QoS model (based on OMG, QoS and FT [51]) to describe a perspective at the application design level, as well as an abstract language for ensuring consistent support for designing distinct aspects of QoS. IoTA-MD has a very limited scope, for example, the goal of abstraction in IoTA-MD is to describe QoS attributes early in the IoT system modeling process.

AutoIoT, in contrast to the approaches mentioned above, does not support any custom domain-specific language. Users in AutoIoT can model IoT systems using a simple JSON description. According to the authors, during the modeling phase of AutoIoT, developers only need to use technologies that are familiar with JSON representation and a general programming language, which reduces the learning phase because they do not need to learn new concepts of a domain-specific language. The above-mentioned MagiDrawbased approach [41] provides a SysML profile for abstraction, allowing for the creation of high-level functional models of the specific Arrowhead SoS application.

3.2.2. Code Generation for Heterogeneous Platforms

MDE automation enables the management of heterogeneous technologies in IoT by automatically transforming models and generating code for specific technological platforms. In this section, we summarize and evaluate the approaches' code generation capabilities. Papyrus for IoT adds automatic code generation support to two solutions: Prismtech's Vortex [52] and MicroEJ's operating system [53].

The Eclipse 4diac IDE can generate C++ code that can be used in the 4diac FORTE development process. The 4diac FORTE is a portable implementation of an IEC 61499 runtime environment designed for small embedded control devices. Unlike Papyrus, 4diac FORTE supports a diverse range of operating systems, boards, and PLCs [54].

The device information models in Eclipse Vorto are based on the Eclipse Modeling Framework (EMF) [55], which allows code generators to generate code in any language, such as XML, LUA, Java, or C/C++. The transformation process in FRASAD takes the model as input and generates the equivalent code for the selected target platform automatically (operating system and hardware). There is no information available about the target platforms that FRASAD supports.

ThingML is made up of an abstract framework and a collection of ready-made code generators for three languages (C/C++, Java, and JavaScript), as well as several libraries and open platforms (e.g., Arduino or Raspberry Pi). ThingML components in an IoT application are distributed across multiple heterogeneous platforms, each with its own code generator. ThingML is distinguished by its support for specific code generator plug-ins that enable the generation of communication and message exchange between components on different platforms.

IoTA-MD does not support code generation; the authors only mention the development of transformation programs (model-to-text) as future work. Through internal model-to-model and model-to-text transformations, AutoIoT can generate ready-to-use IoT server-side applications. The above-mentioned MagicDraw-based approach [41] supports generating a JSON description from the model, which can then be transferred into the Arrowhead Management Tool.

3.2.3. Real-Time Models to Supervision and Monitoring of Running IoT Systems

Real-time models can help with monitoring and modifying the behavior of an IoT system at runtime in response to changes in the system. Modeling techniques can now be used during runtime, taking them beyond the design and implementation phases.

Supporting models at runtime is still uncommon in MDE-to-IoT approaches, with only Papyrus for IoT, Eclipse 4diac, and the previously mentioned MagicDraw-based approach [41] supporting real-time models and monitoring. Papyrus for IoT enables the use of development-time models to monitor running system states. Papyrus' ecosystem enables monitoring of micro-service states as well as starting and stopping them from Papyrus. The ARTiMon [56] monitoring tool can also check real-time properties at runtime.

At runtime, Eclipse 4diac provides features for monitoring the data and event variables of function blocks. The MagicDraw-based approach [41], includes a validation module based on VIATRA [57]. The validation module can check well-formedness criteria during both design and runtime.

3.2.4. Lessons Learned

In recent years, there has been an increase in the number of MDE-to-IoT approaches. We identified the main challenges in the field of model-based IoT in this chapter, and we evaluated several modeling frameworks based on the identified challenges and their solutions. The comparison and evaluation of MDE-to-IoT approaches is depicted in Table 2.

Table 2. Comparison of MDE-to-IoT approaches.

Approach	Abstraction	Code Generation	Real-Time Models
Papyrus [27]	UML use case diagram, SysML requirements diagram, Extension of MARTE	Automatic code generation to Prismtech's Vortex and MicroEJ	Using development-time models to supervise running system states
Eclipse 4diac [30]	Function Block Diagram, Execution Control Chart, Structured Text	Generating C++ code, which can be included in the 4diac FORTE development process	Monitoring the data and event variables of function blocks at runtime
Eclipse Vorto [31]	Graphical DSL, Textual DSL	Device information models are based on EMF, which empowers code generators to generate code in any language	Not supported
FRASAD [32]	Rule-based model, Textual DSL	Takes the model as input and automatically generates code for the selected target platform	Not supported
ThingML [33]	Arhictecture models, Statecharts, ThingML's action language	Abstract framework and a set of ready-made generators for three languages, several libraries and platforms. Generating communication and message exchange between components on different platforms	Not supported
IoTA-MD [37]	Domain model, Information model, Perspective model, QoS mode	Not supported	Not supported
AutoIoT [39]	JSON description	Generation of ready-to-use IoT server-side applications through internal model-to-model and model-to-text transformations	Not supported
Approach based on MagicDraw [41]	SysML profile for Arrowhead SoS design	Generating JSON, which can be imported into the Arrowhead Management Tool	Validation module based on VIATRA to check rules both design and runtime

4. 5G Functions and Features to Support the Information Flow within Industry 4.0

Production companies around the world are vigorously adopting smart manufacturing and have started integrating 5G-related technologies in the industrial field. Beside making production lines flexible and efficient, the general aim is to improve safety and reduce maintenance costs, as well.

The goal of smart manufacturing is to design an intelligent factory capable of self-sensing, completing complex calculations, processing data, synchronization, and independently establishing cooperation between devices. In addition, the best decision to complete complex operations can be taken without human intervention [58]. 5G-related technologies, combined with artificial intelligence solutions, cloud/fog computing and the Industrial IoT (IIoT) will achieve a new integrated smart business ecosystem [59] in the near future.

Well-known estimations from Ericsson is that around 4.1 billion cellular connected IoT devices will use 5G technology by the end of 2024 [60] and 4.4 billion by the end of 2027 [61]. The International Telecommunication Union Radio-communication Bureau (ITU-R) has defined three main 5G application scenarios [62]. These are enhanced mobile broadband (eMBB) for high-bandwidth demanding services (e.g., augmented/virtual reality, distance education, online 4K HD video, etc.); ultra-reliable low-latency communication (uRLLC) for densely connected devices requirement (e.g., industrial automation, intelligent storage and transportation, smart cities, etc.); and massive machine-type communications (mMTC) for delay-sensitive services (e.g., mission-critical application, self-driving car, etc.). In general, those 5G capabilities that make eMBB, mMTC, and uRLLC possible not only enhance the endpoint density, throughput, and latency requirements of the Industrial Internet of Things but also make it more efficient, reliable, and stable.

6G functions and features are not yet defined at this stage; rather, the requirements and visions are defined [63,64]. These build upon the communication at the tera-Hertz bands, supported by non-orthogonal multiple access (NOMA), fog and edge computing, artificial intelligence-based technologies, blockchains, and quantum communication, just to mention a few. The expectations are that tactile internet becomes a reality (due to extremely low delay, high reliability and high throughput communication), with real AR/VR capabilities, ultra-high endpoint density and efficient fulfillment of mixed requirements (slices). Digital Twins (DT) and handling Cyber-Physical Systems are also key application areas for 6G [65]. For the time being (without discussing the exact technologies leading there) we can plan the new DT and CPS applications, which should count on the requirement fulfillment of 6G systems in relation to latency, throughput, reliability, positioning accuracy [66] and endpoint density.

The flow of information in the automation industry can be depicted according to hierarchical ISA-95 [67] or the RAMI 4.0 reference models [68].

The RAMI 4.0 is a 3D model (shown by Figure 5) describing all vital aspects, including all stockholders of Industry 4.0. In this section, we are interested in the communication layer of RAMI 4.0 [69], which describes the integration and coexistence of industrial networks according to their timely requirement and connection types. Figure 6 gives an idea about the information flow in five-layer industrial automation stack [70], covering all crucial aspects of RAMI 4.0, which will be explained in the following sections.

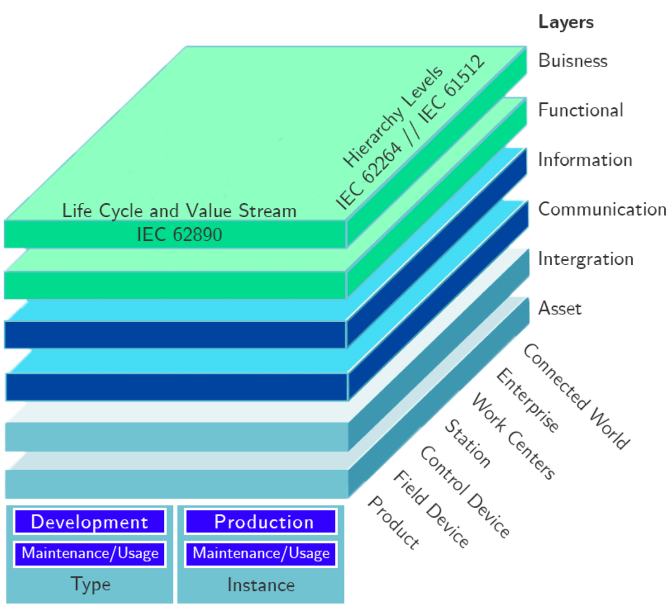

Figure 5. Reference Architecture Model Industries 4.0 (RAMI4.0) [68].

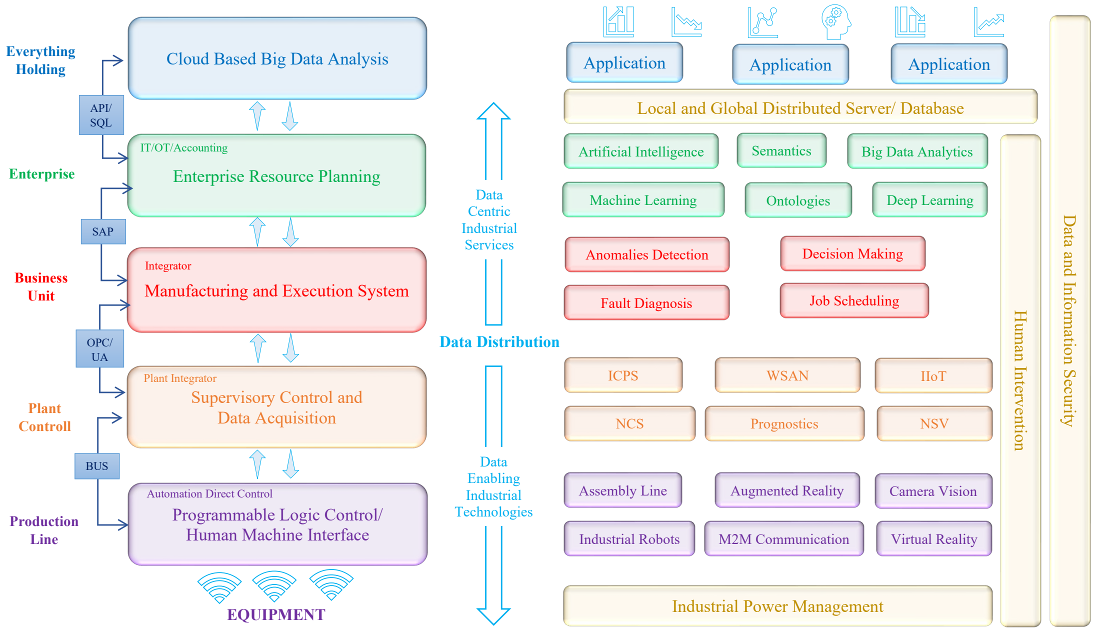

Figure 6. Industrial Automation Stack with its underlying technologies [70].

4.1. Communication Requirements in MES and ERP Systems

ERP is an integrated system application that manages and runs all the typical business management software. ERP is a system of systems that conducts all the core processes required to operate a business: accounting, finance, production, HR, supply chain, services, procurement, and others, including performance management for companies. It creates a knowledge base and integrates the data into new tools in a logical way, which gives all cross-business processes a real-time summary.

Meanwhile, MES is an information system, responsible for all the data flow in a typical industrial plant, connecting all the complex manufacturing components for monitoring and control. It ensures the effective execution of manufacturing operations to improve productivity and throughput. The goal of MES is to track and gather accurate real-time information of a complete production life-cycle to understand the current condition of a manufacturing plant that helps in making suitable decisions for optimization and to improve the product output. In Table 3, certain types of MES systems and their operational requirements and characteristics are listed.

In recent years, Abstract Knowledge-based Automation has been a significant advancement in factory engineering and control science to support real-time decision making in ERP and MES systems. Articles [71–73] describe the main issues faced by knowledge-based production systems to assist factory engineering and knowledge-based technology management. In contrast to decision support, there are multiple use cases when the latency requirement is less strict; however, the estimated device density is much higher than in the previous case, of data acquisition, data exchange, and visualization.

Data acquisition is the sampling process of signals that calculate physical conditions in the real world and transform the resulting samples into digital numerical values that can be tracked by a computer [74–76]. A volume of MES research was conducted to incorporate ERP and physical operating systems to develop a fully automated and integrated manufacturing management environment [77–79]. The papers [80,81] illustrate the requirements and challenges of handling distributed output in a multi-company supply chain and further processes them as characteristics of new IT systems.

Table 3. Requirements for manufacturing and execution systems.

MES Type	Latency (MS)	Reliability	Availability (%)	Device Density	Ref.
Data acquisition	50	10^{-3}	99.99	10,000/plant	[74–76]
Data exchange	50	10^{-5}	99.999	1000/km^2	[77–79]
Decision support	1	10^{-9}	>99.9999	5–10/m^2	[71–73]
Visualization	10–100	10^{-9}	>99.9999	6–8/m^2	[80,81]
App interfaces	200–5000	10^{-2}	95.0	4000/km^2	[82]
Production	5	10^{-9}	>99.9999	6–8/m^2	[83–85]
Logistics	<100	10^{-3}	99.9	3000/km^2	[86]
Enterprise	2	10^{-9}	>99.9999	5–10/m^2	[87,88]
Operational	0.5	10^{-9}	>99.9999	5–10/m^2	[89,90]
Configuration	1	10^{-9}	>99.9999	5–10/m^2	[91,92]
Integration	4-8	10^{-9}	>99.9999	5–10/m^2	[72,93]

In the field of existing MES device weaknesses, benefits, needs and challenges, specifications are gathered from manufacturing companies and combined with insights from literature. MES features include production tracking and control activities in an organization, making available data on the shop floor and evaluating real-time performance metrics such as the usage of equipment, supply of inventory, and quality status [82]. The usage of MES systems is becoming increasingly common in the field of manufacturing; therefore, they also offer interfaces to a wide range of shop floor systems, they also come with data integration, data analysis, and dashboard generation features [83–85].

The usual restrictions and requirements for MES systems are derived from the typical application types and use-cases. The paper [86] presents a framework to describe the relationship between these aforementioned use-cases such as strategy, structure, and logistics in Industry 4.0 in the sense of a changing world. In the ramp-up process, the complexity of automated production systems results in a number of different priorities that need to be considered. The papers [87,88] represent the underlying optimization problem, which is multi-dimensional with respect to the preparation and management of production processes.

Regarding enterprise production systems, it is worth mentioning that lean production is rapidly being applied by leading manufacturers around the world. As the ongoing improvement cycles of several lean initiatives focus on cost control and improvement in product quality, uncertainty in global markets needs greater resilience and responsiveness without sacrificing cost and quality [89,90]. Today's businesses work in a lively and volatile market environment; therefore, to solve this scenario, businesses seek to understand horizontal and vertical integration of companies and engineering processes leading to real-time enterprise [72,91,92]. The integration of barcode identification and sensing technology [94] with 5G technology contains more information. It increases the efficiency of the ERP system by fast and automatic material processing operation.

4.2. Cloud-Based Big Data Analysis

In Industry 4.0, cloud-based big data analysis is a significant weapon that responsible for the detailed security and business statistics that enhance business organizations' ability to make choices. It examines the knowledge according to the needs of the involved programs, applications and technology. 5G is a leader in promoting low latency and high throughput specifications for highly immersive applications [95]. The main requirements for the efficient implementation and operation of cloud-based big data analysis in 5G [96] are local processing, availability, high data-rate, and real-time interaction. The influence 5G technology in the cloud-based big data analysis is shown in Table 4.

Table 4. The influence 5G technology in cloud-based big data analysis.

5G Functionality or Feature	Hybrid Computing	Edge Computing	Fog Computing	Mobile-Edge Computing
Decision making	-	[97–105]	-	[97–105]
Data analysis	[104,106]	-	[106]	-
Local computation	[104–107]	[97–103,108–111]	[106,108,109]	[97–103,105,106,110,111]
Local storage	[106]	[98,109,111]	[106,109]	[98,106,111]
Energy efficiency	-	[97,101,108,110]	[108]	[97,101,110]
Quality of Service	[104–107]	[98–106,109]	[106,107,109]	[98–103,105,106]
Network function virtualization	-	[100,103,109]	[109]	[100,103]
Software-defined networking	[107]	[102,103,109]	[107,109]	[102,103]
Low latency	[104–107]	[97–103,108–111]	[106–109]	[97–103,105,106,110,111]
Resource management	[105,107]	[101,102,109,110]	[107,109]	[101,102,105,110]
Data management	[105,106]	[97,99,100,102,111]	[106]	[97,99,100,102,106,111]

In order to utilize the benefits of 5G, there are many proposed solutions for different service types and computing technologies (hybrid, edge, and fog). Separate modulation schemes [108], including 64 quadrature amplitude modulation (QAM), 16 QAM, phase shift keying (PSK) and quadrature phase shift keying (QPSK), are used to compare energy efficiency between cloud computing and fog computing in 5G to suggest an energy-efficient model to increase average user throughput and energy consumption. The paper [107] offers a cross-layer resource management mechanism between optical network and fog computing over fiber networks to implement delay specifications for edge servers. An architecture that enables edge servers to provide with caching, computing, and communication capabilities are proposed in [109] to enable content and service providers to deploy closed features, facilities, and content of their mobile equipment. A fiber, wireless (FiWi) connectivity architecture was implemented in [101] to enhance MEC services. A virtualized multi-access edge computing architecture is proposed in [100] to maximize the usable bandwidth and to intelligently reduce end-to-end delays on IoT.

Besides the improvement related to the direct transmission speed and latency, there are numerous 5G features that can enhance performance and overall quality of service. In order to perform energy-efficient collaborative tasks, a D2D architecture is suggested for a large number of mobile equipment in [110], while [111] implements a predictive and constructive caching approach to decrease peak traffic demands. An application-aware traffic redirection mechanism for MEC is proposed in [99] to minimize response time and use of bandwidth, meanwhile, the nearest edge server autonomously develops MEC services to provide mobile equipment with seamless QoS for video streaming [98]. Paper [97] provides an energy-aware discharge architecture, whereby each mobile equipment determines whether to perform or discharge computational tasks to the Multi-Access Edge Computing (MEC) server to reduce energy consumption.

High level features, such as SDN, is used to dynamically manage a community of neighboring vehicular nodes in order to improve control over networks and their resources in vehicular networks [102]. In [103], in order to achieve the delay requirement of 5G, a nonstandalone (i.e., disconnected from the Internet) MEC-based architecture for mission-critical public safety services is presented. In [106], a mobile edge and fog computing architecture based on D2D is implemented to allow collaborative computing that performs tasks on more than a single platform or paradigm to enhance MEC. A real-time, context-aware, service-composition, and collaborative architecture is proposed in [104,105] to provide a fast composite service that consolidates several services enabled by the collaboration of various hardware and software with different capabilities.

4.3. Programmable Logic Control (PLC) and Human Machine Interface (HMI)

The Supervisory Control and Data Acquisition (SCADA) systems is the main controlling system of a factory, which regulate and control all the complex operations of a typical industrial plant. The SCADA systems confide on embedded HMI components for all the efficient operations. The PLC connected with HMI, to assist HMI to integrate with a manufacturing plant. The HMI display the data received from PLC to get input from users.

For complex manufacturing industries using 5Gs, eMBB can be crucial to create intelligent manufacturing for real-time monitoring, cloud-based operation and management, service-oriented technologies, and data streaming-based assembly maintenance [112]. All these requirements can only be achieved by the higher communication rate of eMBB.

Academia and industry researchers are continuously working on the development of eMBB. The efficiency of the spectrum and simultaneous connections is improved by developing a non-orthogonal multiple access scheme [113] using pattern division multiple access (PDMA). The eMBB control channel is improved using polar codes with a joint successive cancellation list decoding method [114] using the hash-based cyclic redundancy check (CRC). The eMBB's bandwidth, coverage, as well as signaling and spectral efficiency are improved using coding schemes of [115] in terms of bit error rate (BER), block error rate (BLER), flexibility, and computational complexity. The multipath high channel protection along with low latency and high spectrum efficiency is achieved in [116] using a flexible data frame based on Generalized Frequency Division Multiplexing (GFDM).

The Industrial IoT-driven advanced manufacturing system, which uses the network of networks system for remote controlling, accessing, and manipulating object process in real-time, same as the human being does, requires 5Gs mMTC [117]. The volume of data generated by densely deployed sensors in the manufacturing industry is a challenging hindrance in the implementation of IIoT, which may be overcome by 5G's antenna array technology [118,119].

The 5G mMTC overhead feedback signaling is enhanced by the [120] compressed sensing-based ACK feedback (CSAF) scheme using grant-free data transmissions (GFDT). The Neighbor-Aware Multiple Access (NAMA) protocol of [121] is scalable and improves heterogeneous communication in mMTC. It is an energy-efficient protocol that improves traffic load and system throughput. With a stable and efficient group-based handover authentication and re-authentication protocol [122,123], the protection against malicious attacks on mMTC in 5G wireless networks is improved. The huge multiple-input multiple-output (MIMO) is an extension for groups of transmitter and receiver antennas for increased spectrum quality and throughput is the key technology for mobile 5G distribution [124,125]. Huawei and NTT DOCOMO have conducted a large-scale field trial to evaluate the feasibility of massive MIMO to evaluate the efficiency of linear, nonlinear, and hybrid precoding multi-user MIMO schemes [126].

The 5G's uRLLC is mainly designed for areas that require incredibly accurate, sensitive, high data transmission, and low latency instruction transmission in machine-to-machine interaction [127]. 5G communication networks are decentralized portable data centers deployed at the edge of networks to perform localization requests to fulfill uRLLC's ultra-low-latency criteria.

The small data packet transmissions to improve the 5G uplink are well adapted for uRLLC scenarios using the collision-free and contention-based radio access protocol [128]. Theoretical queuing analysis and system-level simulations of Qualcomm [129] are used to support 5G uRLLC services. The efficiency and performance of industrial wireless sensor networks are improved by the hybrid multi-channel [123,130,131] schemes, which integrates a large number of nodes using multi-channel diversity. Using an effective physical layer protection method [132] to secure the transmission of OFDM-based waveform, the security and reliability of 5G's uRLLC services is enhanced.

4.4. Supervisory Control and Data Acquisition (SCADA)

SCADA systems were designed to allow operators to track the machines in operation with an effective notification control room and delegate individuals. SCADA is responsible for coordination between substations and control rooms, organizing, and monitoring actions. It can automatically control all sorts of industrial processes. It is a real-time process that communicates directly via HMI and PLC with industrial automation plants to capture and collect all the event log data. The characteristics of various industrial automation types regarding SCADA systems are shown in Table 5 along with their 5G communication requirements.

Table 5. Communication requirements in industrial automation.

Automation Type	Cycle Time (CT)	Data Rate	Payload	Jitter	Number of Nodes	Node Mobility	Refs.
Packaging Machine	∼1 ms	∼1 Mbps	40 B	∼1 µs	∼50	∼20 ms	[133–136]
Machine Tool	∼0.5 ms	∼1 Mbps	50 B	∼1 µs	∼20	∼20 ms	[137–139]
Printing Machine	∼2 ms	∼1 Mbps	20 B	∼1 µs	∼100	∼20 ms	[140–142]
Controllers communication	4–10 ms	5–10 Mbps	∼1 KB	∼1 µs	5–10	-	[143–146]
Closed-loop supply chains	10–100 ms	-	few Bytes	1–10 ms	10–1000	low	[147–149]
Process monitoring	50 ms	-	-	-	∼10,000	low	[150–153]
Plant Asset	50 ms	-	-	-	∼10,000	low	[154–156]
Precise co-operation	1 ms	∼10 Mbps	40–250 B	∼50% of CT	∼100	∼50 kmph	[157,158]
Machine Control	1–10 ms	∼10 Mbps	40–250 B	∼50% of CT	∼100	∼50 kmph	[159–161]
Co-operative Driving	10–50 ms	∼10 Mbps	40–250 B	∼50% of CT	∼100	∼50 kmph	[162,163]
Video over remote control	10–100 ms	∼10 Mbps	15–150 B	∼50% of CT	∼100	∼50 kmph	[164,165]
Traffic management	40–500 ms	∼10 Mbps	40–250 B	∼50% of CT	∼100	∼50 kmph	[166–168]
Safety Panels	4–8 ms	∼5 Mbits/s	40–250 B	4 ms	4–8	medium	[169,170]
Augmented Reality	∼10 ms	-	20–50 Mbits	-	vary	low	[171–174]

The numerous categories of active and intelligent packaging systems in the industrial automation field are constantly evolving in response to the increasing challenges of modern society. This type of automation plays a major role in manufacturing, and the related requirements are the most strict ones [133–136]. Machine Tools 4.0 has had a huge effect since the industrial revolution in productivity in the manufacturing sector, and in most cases, it has very similar characteristics to the ones of packaging [137–139].

Additive manufacturing technology has been highly oriented in recent years with its strong capability in the manufacture of complex geometry and great suitability for personalized product manufacture. Researchers have recognized the main role of additive manufacturing in leading next-generation manufacturing, and extensive research has been conducted on various aspects, including product design, process growth, material modeling and many others [140–142], not to mention machine learning-based solutions [175]. Regarding the communication requirements, this type of automation shares the same characteristics as the aforementioned ones.

Logistical task and processes within are often included in the Closed Loop Supply Chain (CLSC), Industrial Process Monitoring (IPM) and asset management. CLSC management is a big enabler in value-creating networks for sustainability. Due to several obstacles, CLSC implementation challenges, especially in an emerging manufacturing hub, are discussed in [147–149]. The evolution of IPM developments over time are briefly referred in [150–153] with more focus on data-driven approaches. Asset Management includes factory equipment maintenance, which ensures that the equipment performs the necessary amount, at the desired standard, as safely as possible, and still meets the expected cost-effective lifetime [154–156]. The most important requirement regarding the aforementioned process is the (huge) number of nodes.

Since the business world is constantly evolving, for more confident decisions, dynamic environments, full of uncertainties, complexities, and ambiguities, require precise cooperation [131,157,158]. Industrial networks comprise a broad range of devices such as sensors, PLCs, or HMI, which ultimately collect real-time production chain data and then issue control commands to remotely control the entire operation [159–161].

In contrast to the previous process, are co-operate driving, remote control, traffic management and safety features, and considered classic automation tasks. One of the main technologies that enable vehicles to be powered in a cooperative manner to attain system-wide benefits is cooperative longitudinal motion control [162,163]; meanwhile, Video over remote control sends data to data processing systems from systems that track and control the physical environment, in which cloud computing has proven to have powerful resources to meet processing requirements [164,165]. The paper [166–168] introduces an engineering proposal for techniques to model typical sources of traffic to be found in industrial networks. The studies in [169,170] investigate the link between industrial robot adoption and workplace injuries using safety panel data used in manufacturing industries. Augmented Reality (AR) is a mechanism in which the real or the physical world is augmented by computerized knowledge. This allows us to better understand the method of various (complex) physical-world tasks. There are various papers [171–174] that have assessed the impact of Augmented Reality (AR) and its usability through systematic literature reviews of actual industrial processes. The development of an open source controller interface for Industry 4.0 based on RAMI 4.0 and OPC UA protocol is described in [143–146]. The typical requirements of such tasks involve real-time operation and mobility management that is able to handle the objects moving up to 50 kmph.

4.5. Lessons Learned

MES and ERP systems as well as other coupled services lay in the business and enterprise level of the Industry 4.0 automation stack, therefore they mostly rely upon the software stack itself. However, due to latency and data rate requirements, communication solutions are key factors within this field. The most important driver in this field is real-time decision making and controlling the production plane. These require real-time data gathering and processing, as well as feedback and control mechanisms that are flexible in their communication methods. To enable such a real-time operation, 5G features such as very low latency, high datarate, and network slicing can be utilized in each level of the automation stack. The most important parts of the stack that were discussed before is (i) the SCADA systems, (ii) low-level subsystems such as PLC-s, HMI-s, and (iii) Cloud level, where 5G can be used to ensure that the system meets the requirements for specific applications.

5. The Telco Cloud Enabled 5G Applications

Globally, the use of smart devices and data-hungry services has increased in recent years. This is especially true now that the Internet of Things is putting a lot more strain on telecom networks. Despite the fact that traditional telecom operators still want to increase their income and steak, they are unable to easily find ways to expand their networks and valued services [176]. While 5G provides answers to various IoT requirements [70,177], there are additional opportunities in QoS-controlled end-to-end slicing; in addition to controlling the performance of the radio network, these operators should also be able to control the performance of the cloud. The authors of [178] provide a thorough survey of 5G network slicing, including a taxonomy of related terms, architecture comparisons, and a list of future challenges.

To meet new types of customer needs, telecom operators are establishing virtualized cloud platforms capable of ensuring upkeep for services with high QoS demands. This so-called cloudification or Telco Cloud approach allows telecom operators to adopt a new perspective, shifting away from the traditional categories of wireline, wireless, voice, text, and web servicing toward cloud-based infrastructures and slice-defined servicing [179–181]. With the Telco Cloud design, telecom operators can intelligently manage both IT foundations and network assets in order to adapt to dynamic application requests and build an open platform for growing new services. According to [182], the Telco Cloud aims to meet the needs of telco-grade networked services through a distributed, flexibly configurable, virtualized cloud approach.

There were several reasons for the shift away from hardware-oriented traditional telecommunications networks and toward all software-oriented IP networks. One of the primary motivators is the possibility of using commercial IT hardware as a platform, owing to the cost efficiency and combined experience required to operate and maintain the hardware devices. The growing interest in decoupling hardware and application software necessitates a greater use of virtualization. Aside from IT-grade hardware, the telecom world has been evolving towards new environments that now include 5G New Radio and evolving packet core, as well as private and public clouds [183,184].

This chapter will present an architectural view of Telco Cloud, as well as highlight related technologies. The main differences between the Telco Cloud and IT cloud will be highlighted, and some Telco Cloud applications will be showcased.

5.1. Architectural Overview

The cloudified network, according to Cisco [185], will be fully virtualized from Core to RAN, with end-to-end automation for both network and services. Radio access will initially consist of 4G LTE (macro and small cells) and Wi-Fi, with 5G radio technology in the works. This virtualized Telco cloud architecture, as shown in Figure 7, will be capable of delivering a wide range of services such as consumer mobile, narrow-band IoT, rich media, and low-latency services such as augmented and virtual reality.

As clarified in [186], Ericson also proposed a new model for future network architecture. According to Juniper [187], telecommunications networks are evolving from being a connectivity onramp to being a destination. To operationalize the investment in people, processes, and technologies, this transformation requires vision, strategy, and architecture. Juniper, on the other hand, can realize the transformation through innovative Telco Cloud solutions. You will achieve true cloud outcomes such as speed, agility, and scale by leveraging advanced architectures and an end-to-end automation framework to transform the business and monetize the network. In [188], Dell EMC and the 5G Network Transformation, where the term 5G has become a catch-all for the four approaches to technology transformation—Digital Transformation, IT Transformation, Workforce Transformation, and Security Transformation—applied to the mobile network. Dell's 5G strategy is end-to-end, as illustrated in Figure 8. The architectural separation of several clouds communicating with each other is discussed here, as well as how use cases rely on network slicking. This also enforces the architecture's distributed multi-cloud approach, as well as how end-to-end slicing requirements must be met across these cloudified environments.

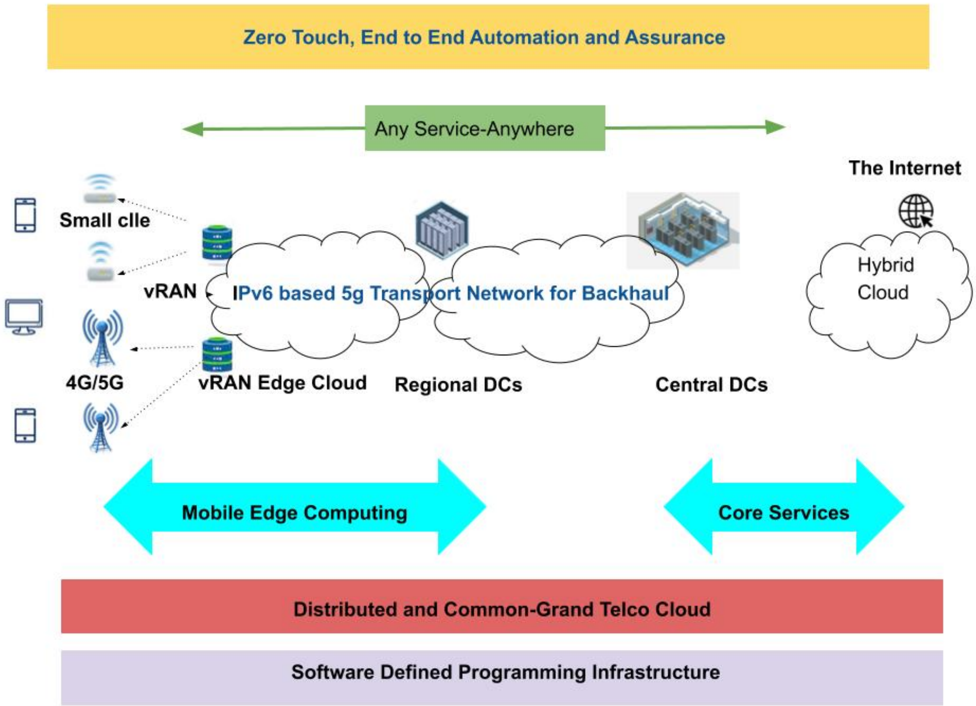

Figure 7. Completely virtualized with a shared and distributed Telco Cloud.

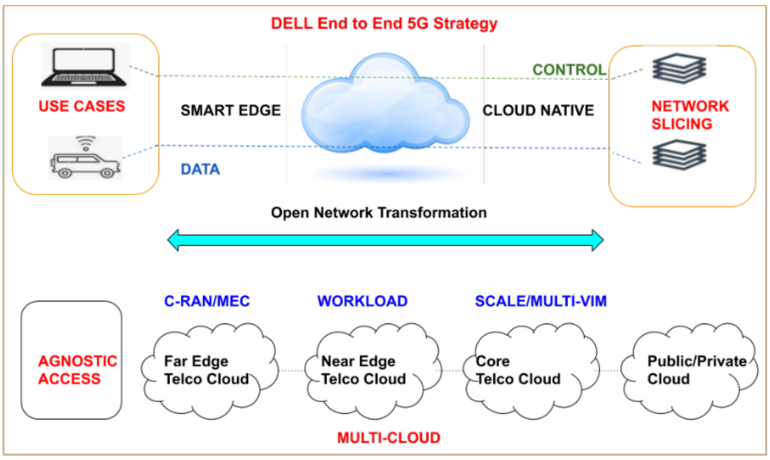

Figure 8. End-to-End DELL 5G strategy.

In [189], the cloud-native can help future-proof telco networks, whereas service providers can cost-effectively deliver a plethora of compelling, revenue-generating services with the right distributed edge cloud platform. There are compelling 5G use cases in transportation, including smart transit and rail systems, autonomous shipping, and autonomous vehicles. Companies are investigating 5G-enabled robotics applications, human–machine interfaces (HMIs), and virtual Programmable Logic Controllers (vPLCs) as part of Industry 4.0. As illustrated in Figure 9, the healthcare sector is also actively investigating 5G for imaging, monitoring, and diagnostics. The architectural separation of the distributed control plane, edge controller, edge worker nodes, and use cases are shown here.

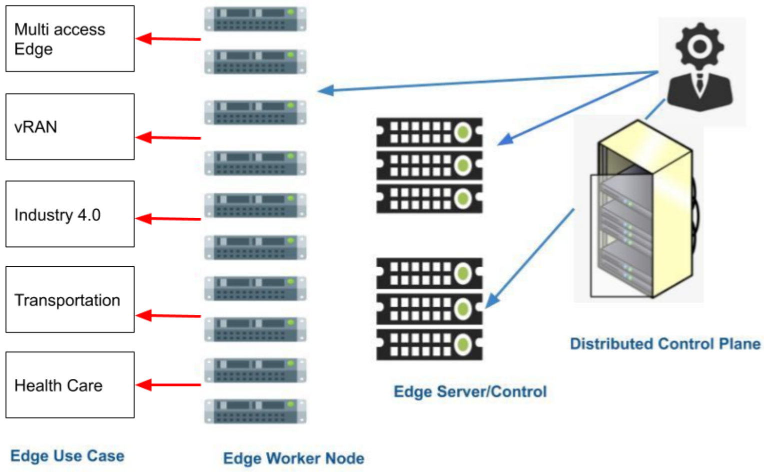

Figure 9. Distributed edge cloud topography.

The authors of [190] present a 5G Telco Cloud Platform, where Telco Cloud Platform combines multi-cloud management, and VMware Telco Cloud Automation for multi-domain orchestration and automation. A new IBM hybrid cloud [191] offers geared toward enterprise 5G and edge computing adoption. The authors in [192] defined Telco Cloud, Network Function Virtualization (NFV), and proposed a Telco Cloud architecture, as shown in Figure 10, which has four layers, as follows:

1. Virtualization Network Function (VNF) Layer;
2. NFV Infrastructure (NFVI) Layer;
3. Operation Support Subsystem (OSS) Layer;
4. Management, Automation and Network Orchestration (MANO) Layer.

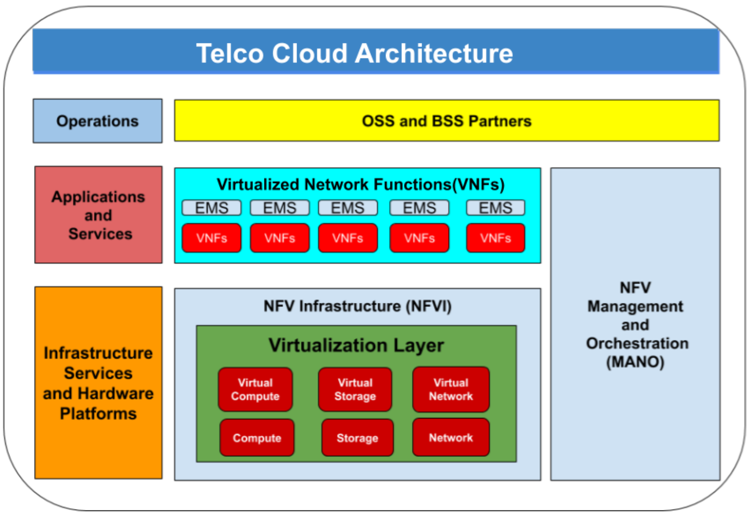

Figure 10. Telco Cloud Architecture.

Advanced flexible architectures for future 5G networks are also presented at [193,194]. Ref. [195] also clarified the definition of the Telco Cloud and its requirements.

5.2. The Benefits of Telco Cloud

There are several benefits for Telco cloud [176,183,196] and the Figure 11 showed some benefits of Telco Cloud:

1. Capability to reduce CAPEX and OPEX costs despite rapid growth in user numbers and network traffic by introducing cloud computing platforms to connect users and applications.
2. By virtualizing traditional equipment and services, the average utilization of telecom equipment is greatly improved.
3. It offers a versatile infrastructure that is highly scalable in order to provide users with highly scalable services.
4. It offers services with high reliability and availability.
5. Energy efficiency.
6. It enhances resource utilization and management.
7. The telco cloud reduces network offloading by processing data closer to the user.

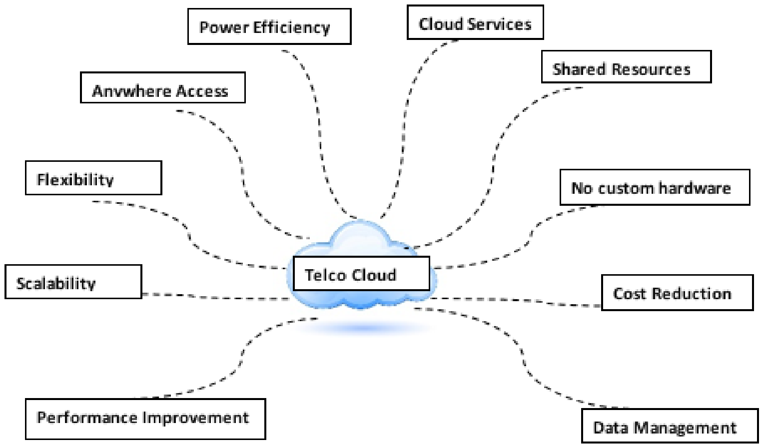

Figure 11. Telco Cloud benefits.

5.3. State-of-the-Art Overview

The paper [183] provides an overview of the transition to Telco Cloud and clarifies the key dimensioning, accessibility plan ideas, and some operability challenges. The transition of telecommunication networks from proprietary hardware-based infrastructure to Telco Cloud introduces new features in terms of service availability, system dimensioning, and operation. These advancements allow for the efficient handling of ever-increasing traffic and the expansion of services. 5G is expected to fully leverage technologies such as network automation, software-defined networking, network function virtualization, and network slicing. These will present new opportunities as well as new challenges for dimensioning and operating 5G networks. The authors also looked at some examples from R&D as well as feedback from real operator networks.

According to [197], fog computing enables a new breed of applications and services that go beyond traditional telecom services, implying a fruitful interplay between the cloud and the fog. As a result, a distributed intelligent platform at the edge that manages distributed computing, networking, and storage resources are required. As a result, the author proposed the TelcoFog as a novel, secure, highly distributed, and ultra-dense fog computing infrastructure that can be allocated at the edge of the Telecom Network to provide multiple unified, cost-effective, and new 5G services such as NFV, MEC, and third-party services (e.g., smart cities, and IoT). They also present a new architecture for providing unified cloud and fog resources for unifying NFV, MEC, and IoT services on top of a telecom operator's network, assisting telecom operators in lowering their total cost of ownership. The TelcoFog architecture is depicted in Figure 12.

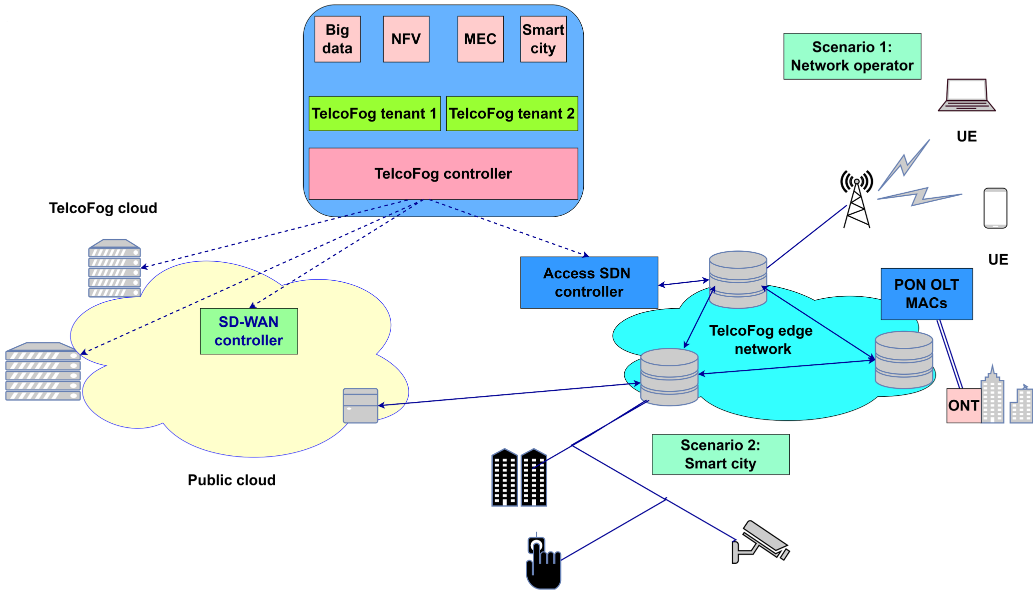

Figure 12. Telco fog architecture.

The authors of [176] discuss the emergence of Telco Cloud Technology, where, by implementing cloud computing platforms, telcos can reduce CAPEX and OPEX costs. Given that the major issue in the telecom industry is the increased cost of CAPEX and OPEX due to the significant growth in users and network traffic, their position is that the deployment of the Telco Cloud platform is required to ensure long-term profitability. The cloud computing model significantly improves average telecom equipment utilization by virtualizing traditional equipment and services as interface between users and applications. They state that the reduction in OPEX is mainly achieved by integrating automation and orchestration into the service management process, thus, reducing manual activities. They also saw the Telco Cloud as enabling a virtual telecom operator concept via an open platform. The rapidly growing measure of cloud-based Virtual Network Functions introduced new concepts for dimensioning, sending activity to the executives, authorizing, and monitoring.

One of the earliest papers to highlight the Telco Cloud concept is [198], where the authors propose a Telco Cloud model as a solution to the hardware integration and management issue. Telco Cloud offers novel options for implementing telco core functions that are both cost-effective and reliable. Virtual telecommunications aims to replace expensive dedicated equipment used to implement several centralized control plane functions and other services with distributed solutions that can be allocated on-demand across a pool of dependable, dynamically contracted computing and networking resources that are easy to manage. The proposed Telco Cloud computing paradigm now includes an appropriate resource management layer. According to the authors, only a subset of applications are compatible with the Telco Cloud platform. If an application does not meet the requirements for distribution, it should be removed from the Telco Cloud. These applications are referred to as legacy software.

The Telco Cloud architecture is divided into five distinct layers, according to [199]. Each of these layers has a few sub-segments that may or may not have partners. These partners are responsible for overseeing the activities of that specific segment. The illustrative model is shown in the Figure 13. Each of these layers contains several subcomponents, each of which may have a different set of stakeholders. These stakeholders are in charge of the operation of that specific component.

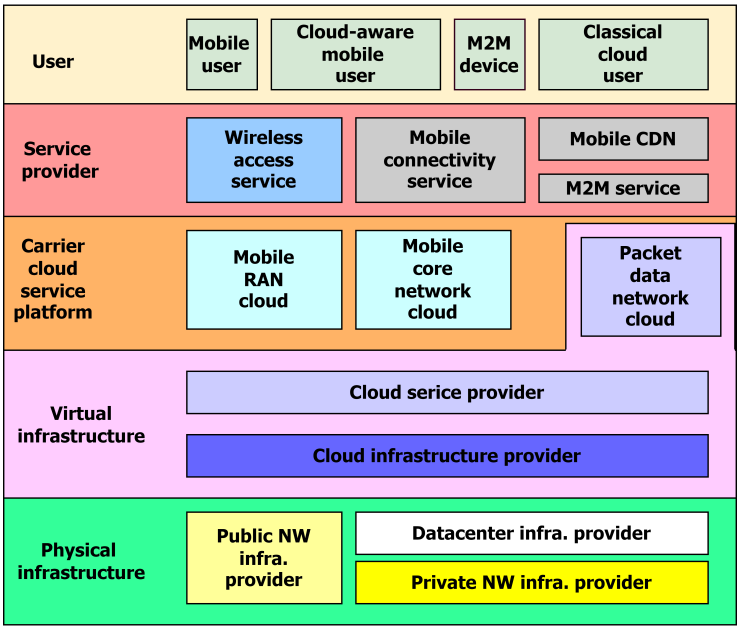

Figure 13. Telco cloud architecture.

- User layer: This layer represents all network-connected devices that do not have to be people.
- The service provider layer: This layer expresses all of the services that are available to users. Services such as mobility, content delivery networks (CDN), and machine-to-machine (M2M).
- The carrier cloud service platform: This layer virtualizes the upper layers, such as Mobile RAN cloud, Mobile core network cloud, and packet data network cloud.
- virtual infrastructure layer: This is split into two stages. The first is a cloud infrastructure provider, who offers a clouding environment devoid of physical components. The second is a cloud service provider, which acts as a link between virtual layer and upper layer applications.
- The physical layer: It includes the network's hardware entity, which contains cabinets, cooling, and electricity distribution, among other things.

The authors of [196] proposed a meta-model for the Telco Cloud system. The model can be used to reenact various configurations, observing the behavior of a framework from an execution and cost standpoint. They discovered that a large scale testing environment for recreation of an entire Telco Cloud climate would be financially costly. However, a limited scope recreation framework cannot detect all potential examples of client behavior. They propose two types of data centers (DC), as illustrated in Figure 14. The first is Remote DC, which is a large facility located relatively in the center of the network, far away from access networks. The second type is Proximal DCs, which are smaller facilities located on the network's edge, close to access networks and end-users. Furthermore, when compared to the traditional model, access networks and cloud infrastructure are quite closely integrated. Because proximal DCs consume the majority of capacity, remote DCs are used for coordination and control.

The authors of [200] observed how a Telco Cloud environment can contain network service functions and how a proof-of-concept model can be built on top of the Cloud4NFV platform. This paper clarifies that building a network function is based on over-provisioning to ensure appropriate service levels based on estimated peak traffic and the accepted risk of redundancy model where a single fault can bring the service down. While virtualization has matured as a technology, carrier-grade reliability and performance expectations have also reached feasibility. As a result, the anticipated consolidation of the traditional model and virtualization will result in significant cost savings.

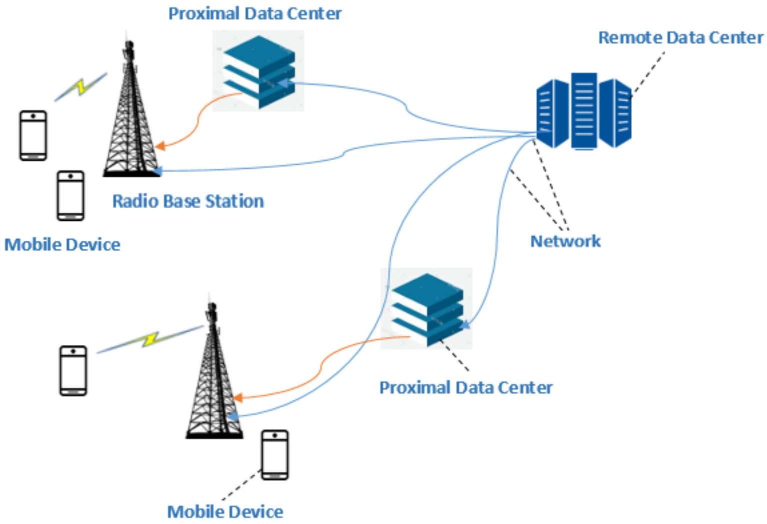

Figure 14. Data Center-proposed types

5.4. Telco Cloud vs. IT Cloud

Table 6 clarifies the main differences between Telco cloud and IT cloud as stated in [183,201,202].

Table 6. Comparison of Telco Cloud and IT Cloud.

Parameter	Telco Cloud	IT Cloud
Platform type	Open and scalable platform	May utilize seller restrictive advancements.
Terminology	Telco Cloud commonly refers to a Private Cloud deployment within a Telco/ISP environment that hosts Virtual Network Functions (VNFs) of the Telco/ISP Network utilizing NFV techniques	Related to an enterprise workload and is a private cloud deployment. IT Cloud provides cloud based services to render enterprise requirements.
Applications	Telecommunication applications	User applications
Latency	Very low latency 5 ms	Low latency 1 s
Availability	High availability 5–7 nines	High availability 3 nines
Throughput	Very High throughput 100 Gbps	High throughput 10 Gbps
Related technologies	OSS, VNF, NFV, SDN	Virtualization, IT workload
Reliability	Very high	High
Performance	Very high performance	Lower performance
Arrangement	Distributed Data Centers	Centralized Data Centers
Security	Very high	High
Oversubscription and CPU Allocations	Ratios are typically 1:1	Ratios may vary from 8:1 upto 16:1

5.5. Telco Cloud Industrial Applications

The emergence of Telco Cloud in the modern era is a marvel because of its tremendous importance in the development of various industries based on automation, and we will discuss some of the applications of Telco Cloud in the field of industry here.

5.5.1. Video Analysis and Monitoring

The authors [203] propose that a system that demonstrates that real-time video analytics is the killer app for Telco Cloud. The reduction in camera prices and the increase in network speed have resulted in a significant increase in video analysis applications and the deployment of large numbers of camera networks. If the video analysis process is moved to the edge, it will help to reduce energy consumption and increase data processing [204].

5.5.2. Big Data Analytic

In [205], the Telco Cloud, can be used to analyze big data at the network's edge, potentially saving bandwidth and energy consumption rather than wasting a large amount of bandwidth and energy when that large amount of data is sent to the core network to be analyzed.

5.5.3. Smart Transportation

Nowadays, cities face numerous challenges, including a lack of public transportation, a limited number of parking spaces, and pedestrian and driver safety [205]. Telco Cloud can be used to automate traffic at the network's edge by collecting real-time data from devices such as cameras and various sensors installed on both sides of the road, allowing for full control of traffic and the ability to alert drivers to congested areas or dangerous roads, as well as assisting in the smart parking process, using sensors to determine available parking spaces. There are numerous Edge Cloud use cases, including [177,204,205].

5.5.4. Robotics

Due to its reliance on decentralization in processing, Telco Cloud provides high speed in data processing and decision making, where robots can be controlled in real-time using Telco Cloud remotely, obtaining very high accuracy in all industry sectors [206,207]. This is the ability to fully control robots or robotic arms, issue commands, and collect data from sensors connected to them accurately and safely in places where humans cannot reach.

5.5.5. Localization and Tracking

The collaboration of the Internet of Things and Telco Cloud is a critical factor in localization and traceability, as it is possible to achieve very high accuracy in localization and real-time tracking of targets and their identifications [208]. Localization is important in knowing the location of robots or industrial equipment in the event of natural disasters or theft, as well as in smart driving operations in self-driving mechanisms [209].

5.5.6. Predicting Disasters

Telco Cloud enables the early prediction of disasters such as earthquakes, volcanoes, and floods through the accurate and real-time processing of data obtained from sensor groups distributed in various locations such as the seas and underground or carried on drones in the air and connected to the Telecommunications network where these sensors work to collect data. It provides continuous reports on the surrounding environments [208]. As a result, there is the possibility of taking preventive measures before a disaster occurs.

5.5.7. Education

There is a high demand for Telco Cloud-based education, particularly in cases of epidemics such as COVID-19 [210,211]. Telco Cloud can assist in the provision of an advanced and interactive educational cloud environment in which students can attend classes and laboratory experiments from home and access study materials without having to travel to education centers.

5.5.8. Healthcare

Obtains real-time information about the patient's condition, such as blood pressure, heart rate, oxygen levels in the blood, and so on [212] by connecting healthcare equipment to the cloud without the need for the patient to be present in the hospital, and the medical reports on patients are updated on a regular basis. There is an optimal hospital resource investment to avoid unnecessary waste and thus save money. Continuous monitoring of the technical condition of medical equipment to avoid unexpected malfunctions [213] is conducted.

5.6. Lessons Learned

Table 7 summarizes the findings of a group of studies on Telco Cloud technology, as it was discovered that Telco Cloud is the most recent major advancement in cloud technology and a promising technology because it helps reduce the high cost of CAPEX and OPEX. It offers network operators a scalable infrastructure as an open environment for developers, with the cloud serving as a direct link between the user and the applications, and it can be used in a variety of 5G and 6G applications. More emphasis should be placed on research in the field of telecommunications cloud computing. According to the review of related papers, Telco Cloud is a modern technology, where it was noted that the first research paper related to Telco Cloud was in 2011 and that technology is not thoroughly researched; future research should be studied from several different perspectives to get a more paramount view, such as a customer, regulator, or application provider view. Because of the importance of cloud economic efficiency for service providers, cost structure research should be considered. Another critical aspect to thoroughly investigate is Telco Cloud security.

Table 7. Contributions from previous studies on the Telco cloud.

Ref.	Contribution
[183]	Clarifies the essential dimensioning and accessibility plan concepts, as well as some operability challenges, and includes real-world examples.
[197]	TelcoFog can be deployed at the Telecom Network's edge to provide a variety of 5G services, lowering the Total Cost of Ownership.
[196]	There was a proposal for a meta-model for the Telco Cloud system. They propose two types of data centers (DC): remote and close.
[200]	The Telco Cloud model is built on the Cloud4NFV platform, which will result in significant cost savings.
[199]	There are five layers to the Telco Cloud architecture. Each of these layers has a few sub-segments that may or may not have partners.
[176]	The Telco Cloud technology is an open platform that connects users and applications to assist telecom operators in lowering CAPEX and OPEX costs.
[198]	As a solution to the hardware integration and management problem, a Telco Cloud model was presented, in which the appropriate resource management layer was added to the proposed Telco Cloud computing paradigm.

6. Speech Technology in Industry 4.0

The use of mobile data has increased dramatically over the last two decades. Furthermore, Internet of Things devices consume more data than previously. As a result, effective deployment of 5G technological advances has become necessary. 5G offers useful features such as low latency, high speed, reliability, and network slicing. Meanwhile, many challenges accompany 5G implementation, including operational costs, the high capacity of connected devices, end-to-end latency, quality of experience, and data rate [214]. As a result, 5G attempts to implement some technological solutions to increase the network's traffic capacity [215].

In 5G IoT scenarios, human–machine interactions are increasingly based on speech, which is the most natural mode of communication. Speech could be used in a variety of industries, including computer control via natural speech rather than written instructions, IoT, security, and healthcare. In general, people can speak faster and more easily than they can type, resulting in faster communication. This ability may allow people to focus on multiple tasks at once. Cloud-based speech recognition services are used in emerging 5G network-based IoT applications, so we need high accuracy, low latency, noise robust, scalable, and reliable speech services to provide useful and usable solutions.

According to [216], recent voice recognition technology may have a very high accuracy estimated at 99 percent. This means it has progressed to the most advanced technical stage of the process. Because it produces remarkable results, it is becoming increasingly popular among researchers for use in the industrial field. Furthermore, voice-activated speakers are becoming increasingly popular among their users. According to [217], 72 percent of those who own it say it has become a regular part of their lives.

This chapter aims to discuss the state-of-the-art in speech technology in industrial applications using 5G or IoT, as well as the technical design challenges that researchers face when attempting to implement it. Furthermore, we summarize methods and tools, as well as consider future trends.

6.1. Speech in Healthcare Applications

Many studies on the use of voice technology in the healthcare industry have been completed in recent years. The human voice can be used to communicate with devices by doctors, technicians, nurses, and patients. Similarly, emotion recognition-based speech signal analysis could be used in industries to investigate the relationship between worker mood and productivity.

In [214], an emotion detection model in a smart home environment is proposed. It focuses on children, the elderly, and people who are mentally ill, with the primary goal of identifying pain. In these homes, IoT sensors are distributed to record speech and image signals and send them to the proposed system. The system separates the image and speech signals and makes an emotion decision based on the fused classification score. When the system detects pain in these individuals, it notifies the caregivers. The system claims 99.87 percent accuracy in detecting pain. The proposed system is a healthcare application that is based on 5G data transmission and big data analysis.

A 5G-based Cognitive telemedicine system [218] is proposed to share high-quality medical resources between a large hospital and rural, remote areas. The solution's goal is to detect people's emotions and, moreover, to diagnose psychological diseases. The system is composed of three layers, where sensors, devices, and network components are included in the infrastructure layer. The task of the resource cognitive layer is resource optimization in order to achieve a green, reliable, flexible, low latency, and scalable solution. The data cognitive engine is built on big data, machine learning, and deep learning. The main goal is to detect the patient's emotional state in order to diagnose psychological diseases. In order to facilitate application establishment, large-scale implementation still needs to address some issues such as privacy, data security, more refined intelligence, and API.

A lip-reading driven audio-visual hearing-aid is presented in [219], which outperforms audio-only versions in noisy environments but requires significantly more sensor data and processing power. To achieve real-time operation, a 5G IoT network infrastructure with 5 ms latency and 100 Mbps data-rate was required. Audio-visual data must be encrypted on the channel due to privacy concerns. A new light-weight real-time encoding method based on the piece-wise linear chaotic map (PWLCM), chebyshev map, secure hash, and substitution box (S-Box) algorithms is proposed. Speech enhancement is carried out in the cloud. Noisy and visual speech are processed concurrently, and the lip reading model is based on a novel LSTM model, which improves on previous HMM-based models.

Amazon's Alexa and Google Assistant pave the way for task-specific voice interfaces, and in-home healthcare setup [220]. Voice interfaces act as intermediaries between the user and a variety of medical web services. Patients must use natural language queries rather than navigating through complex/multiple web pages, which may be especially useful for elderly and digitally less savvy users. Patients can access medical information, take medical measurements, communicate with caregivers, make doctor's appointments, and receive proactive medical reminders. A diverse range of services can be added to the pool of services. Table 8 recapitulates the mentioned research regarding the problems, techniques, contributions, and limitations.

To summarize, enhanced speech-related services are being developed and made available. Some are still in the laboratory or in the testing phase, but they are very close to being ready for market. However, there is a high demand for dependable speech services, so we can anticipate an increase in the number of solutions and end users in the near future.

Table 8. Summary of speech technology in healthcare application.

Problems	Techniques	Contribution	Limitations	Ref.
Emotion detection model is focusing on pain detection for the elderly	Record and stream image and speech signals of the individual	Up to 99.87% accuracy to detect emotion	To keep the individual's privacy, security should be considered	[214]
Share medical resources between the big hospital and rural areas	5G Cognitive System	The system has an excellent reliability and a good latency	The system has difficulties with security and intelligence	[218]
Audio visual speech enhancement in a noisy environments	low latency 5G Cloud-Radio Access Network, powerful encoding algorithms, IoT, LSTM lip reading model	Novel cloud-based approach for noise reduction	There was not a proposed solution for the big data	[219]
Voice-enabled health services	Amazon's Alexa and Google Assistant	Apply Home healthcare	Further work is needed to add more services	[219]

6.2. Speech in Robotic Applications

Robots have been used in a variety of industries, including welding, painting, packaging, testing, and assembly. Robots are extremely precise, fast, and repeatable. When using these robots in the manufacturing workflow, industrial workers face a number of challenges, including safety and ease of control [221]. Natural voice control of industrial robots is extremely rare due to the extremely high reliability requirements, which is especially difficult in noisy industrial environments. Voice control, on the other hand, would be very useful for workers because it allows them to focus more on the operation. Few attempts have been made to solve the problem in this field, as most are still in the research phase.

Future cooperative robots will be more adaptable and multifunctional. Traditional teaching methods necessitate the use of professional staff and a lengthy training and testing period. Timely training of a collaborative robot is critical because its functionality is more diverse and may change in a short period of time. An online teaching method is proposed in [222]. A depth camera (Kinect) and an inertial measurement unit capture human speech and gestures, respectively. To convert speech and gesture to text, the audio-visual fusion method is used. To map intentions extracted from text to robot instructions, a maximum entropy algorithm is used. The proposed interface has been validated in robot teaching scenarios where operators can govern the robot without requiring any special skills or effort.

The study in [223] looks into voice-controlled industrial medical robots. The components of an HIWIN robotic endoscope holder are shown in Figure 15. The speech recognition system processes the voice signal, and the recognized instructions are transmitted to the robotic endoscope holder via an RS232 connection. The robotic arm's movement is tracked, and it can be calibrated to respond to voice commands. The proposed voice control system has an angular movement accuracy of up to 3.1° for the endoscope.

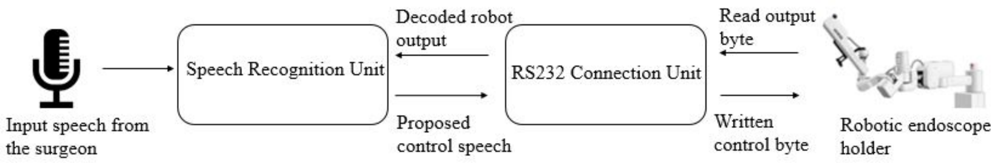

Figure 15. System structure

Ref. [224] investigates controlling robotized cells via a web-based speech-enabled interface. The speech engine is used in conjunction with context-free grammars (CFG). Although semi-natural voice inputs can be used with high recognition accuracy, the user must be familiar with the possible command words or phrases. The language generation is tailored to the scenario of industrial robot control. When compared to local implementation, remote control had no practical delay; traditional keyboard-based control was slightly slower than speech-enabled control, but word error rates must be considered. Table 9 outlines the speech technology in robotic applications regarding the techniques and contributions.

Table 9. Summary of speech technology in robotic application.

Problems	Techniques	Contribution	Ref.
Teaching cooperative robots is a complex process	Audio-visual fusion based on text, intent detection, maximum entropy intent to control mapping	Novel method to teach cooperative multi-purpose robots	[222]
Speech-controlled medical robots	HIWIN robotic endoscope holder with speech recognition	An accuracy of up to 3.1° of angular movement for the endoscope	[225]
Control robots by using speech	Web-based control, speech recognition, context free grammars	Quasi-natural language commands	[224]

6.3. Speech in IoT Applications

SmartHear system [226] is a hearing aid system designed to reduce the effects of noise, reverberation, and signal quality degradation when the speaker and listener are separated by a large distance, such as in an auditorium. It was created primarily to assist students with hearing loss or foreign students who were studying in a noisy environment. A smartphone records the audio signal, which is then transmitted to the listener via Bluetooth or WiFi. Therefore, the room's noise and reverberation can be effectively eliminated, and understanding the spoken information requires less cognitive load from the listener. As an added convenience, automatic speech recognition (ASR) is integrated, allowing the listener to follow the written text on the screen. The system was evaluated subjectively as well as objectively, and the results show that the degradation caused by the speaker's distance can be eliminated using SmartHear.

The smart campus system described in [227] is an application that combines a number of novel technologies. The conversational dialogue system is based on the Chinese word embedding solution, which improves dialogue toleration and semantic interpretation significantly. Emotional labeling of the conversation is also performed, and it is used as an input feature by the neural network-based dialogue engine. Several emotional scoring methods were trained and tested, and GoogLeNet outperformed the others with over 95% accuracy. In domain conversations were used to train the dialogue engine. The integrated system provides information about a Taiwanese university campus via an easy-to-use audio interface.

6.4. Speech with Security Issues

Speaker identification and speech recognition are becoming increasingly important in secure applications such as electronic payments. We must be aware of information security issues and work to mitigate potential threats in this area. In many cases, the human–machine interaction interface of smart IoT devices is natural speech. E-health, smart building control, and Apple Siri are examples of IoT applications that use speech input control (see Figure 16). According to [228], privacy is a serious issue in the used speech services because the audio data and recognition results are transferred unencrypted, making personal data vulnerable. To protect privacy in IoT scenarios, a long short term memory (LSTM) neural network-based secret sharing protocol is introduced.

Figure 16. Smart IoT devices controlled by speech commands.

The accuracy of speech recognition using Kinect sensors may be inefficient and uncertain due to the sensor's random placement [229]. A client-server speech recognition system was proposed to overcome the drawbacks of the traditional Kinect-SDK speech recognition method. Multiple Kinect sensors are linked via TCP/IP, and sensor selection is handled by a decision server. Several decision-making and sensor-placing strategies were investigated. Using multiple Kinect sensors resulted in a 28% relative improvement, while processing time increased by only 13%.

In the 5G network, the number of devices that share information on social media will be enormous. The growing volume of multimedia content necessitates the development of data integrity solutions. In [230], a Speech Watermarking technique is introduced to improve the integrity of sharing speech or audio signals in the 5G wireless network. The Least-Significant-Bit substitution technique is used in this method, which employs the Filter Bank Multicarrier Modulation (FBMC) Technique. The embedded watermark outperformed existing techniques in terms of resistance to various attacks.

Inaudible voice attacks are a threat to speech recognition systems used in smart homes. The use of ultrasound carriers to modulate human voice produces inaudible signals for humans, but speech recognition devices may detect and respond to this. Watchdog is a signal processing-based detection method described in [231]. Environmental signals are being recorded using an ultrasonic microphone. A low level alert is issued whenever a suspicious frequency is detected. The ultrasonic signal is demodulated, and a voice activity detector is used to determine the presence of human voice in the demodulated signal, resulting in a high level alert. To avoid false alarms, ambient noise must be analyzed.

Because of overlapping speech, it is difficult to identify speakers in crowded places such as meetings or debates. Ref. [232] proposed two methods for overlapping automatic speaker identification (OSID) with up to five concurrent speakers. In the first stage, the two-stage method determines the number of simultaneous speakers and then identifies them in the signal. The single-stage method achieves OSID directly in one step by employing a single classifier. Both OSID systems use one-dimensional convolutional neural networks, which outperform multilayer perceptron and Gaussian mixture model-based systems. In a clean dataset, the two-stage system with five speakers has an accuracy of 98.55 percent, while the one-stage system has 95.07 percent.

Speaker recognition in [233], such as the previous one, is based on one-dimensional convolutional neural networks. The method was developed using the Xilinx VC709 platform. The model reduces the computational complexity of ResNet20 by 64% and the number of parameters by 53%, allowing for efficient FPGA implementation. Furthermore, the model can handle speech data of varying lengths.

6.5. Noisy Speech in Industrial Environments

Noise is regarded as one of the most significant barriers to using speech in industrial settings. Many efforts have been made to reduce background noise in speech and to provide robust speech processing. Acoustic and Adversarial Supervision (AAS) is a speech enhancement algorithm proposed in [234] to improve noisy speech recognition while preserving clean speech recognition. To train, both clean and noisy data are used, but unlike traditional methods, clean and noisy audio samples do not need to be paired. It was put through its paces on two noisy datasets: CHiME-4 and Librispeech + DEMAND. According to the paper, AAS outperformed other speech enhancement methods in terms of word error rate.

High accuracy human machine interfaces are required in self-driving cars, but mechanical and electric power equipment noises in electric vehicles can be significant, and they are quite different from traditional vehicles. Therefore, ref. [235] introduced a new method for reducing speech noise for human–machine interaction in electric vehicles. This method for improving speech is based on improved nonnegative matrix factorization (ImNMF), which outperforms traditional nonnegative matrix factorization methods.

The analysis of special signals, such as the sound of a bearing, is critical in industrial scenarios. Finding a faulty bearing in good time can help you avoid costly breakdowns. A noisy environment, such as a factory, engine, or environmental noise, complicates the mission of bearing fault diagnosis. Convolutional Neural Networks (CNNs) were used in [236] to classify bearing faults, and spectral kurtosis filtering was used to reduce the noise in the raw data. The method was tested on the CWRU bearing dataset, and the improvement is detectable at -10 dB SNR.

A wearable MEMS microphone array was presented in [237] to improve speech in a noisy environment. The project's goal is to improve speech recognition accuracy while focusing on motor-impaired people for whom voice is a convenient or, in some cases, the only way to control a computer. The time of audio arrival between the microphones in the array was measured to separate speech from environmental noise. In good SNR situations, the microphone array performs similarly to the single microphone version, but significantly better when SNR is less than 20 dB.

The Cochlear Implant (CI) is an implantable electronic device that replaces the function of potentially damaged inner ear parts. Implementing advanced signal processing in CI devices to enable higher speech intelligibility is a difficult task. To improve speech intelligibility, Ref. [238] implemented a novel deep learning-based noise classifier and deep denoising auto-encoder method. Clinical listening tests were conducted on Mandarin-speaking cochlear implant recipients to evaluate the method. The intelligibility scores outperformed all of the other methods tested.

Voice activity detection methods are used to separate speech from noise. It is used in most speech-related applications, for example, to distinguish speech from background noise or to save processing power. Because signal classification models can be trained on known environmental noises, speech-signal context is important for some voice activity detection methods. Unpredictable noisy environments are investigated in [239]. The adaptive context attention model makes use of context information by implementing a neural network architecture. The results are compared to those of other methods. Deep neural network models performed similarly, but the proposed model only had half or a third of the parameters of the others.

An active noise cancellation setup is described in [240]. A pair of MEMS resonant microphone arrays are used, each with a different resonance frequency. One array covers the frequency range 0.8–5 kHz, while the other covers the frequency range 5–9 kHz. The lower range is used for speech recording, while the upper range is used for noise cancellation. Noise cancellation is implemented and tested using traditional signal processing and deep learning. Speech recognition word error rares are used to assess efficiency. The proposed active noise cancellation algorithm provides a measurable advantage in the −10 to −30 dB SNR range. In general, the measured noise reduction is −10 dB, but at resonance frequencies, up to −25 dB is achieved. Table 10 overviews speech with industrial noise issues about the techniques and contributions.

Table 10. Summary of Speech with Industrial Noise Issues.

Problems	Techniques	Contribution	Ref.
Speech enhancement in noisy environment	Acoustic and adversarial supervision (AAS) algorithm	AAS gained lower word error rate than traditional methods	[234]
Speech enhancement in electric vehicles	Improved nonnegative matrix factorization (ImNMF)	Decrease the effect of noise on human–machine interaction	[235]
Bearing fault diagnosis in industrial environment	Convolutional neural networks and spectral kurtosis filtering	High classification accuracy even in noise	[236]
Speech enhancement with a wearable microphone array	The time of audio arrival measurement	Significantly higher recognition accuracy in noisy environment	[237]
Noise cancellation implemented on cochlear implant devices	Deep learning-based noise classifier and deep denoising autoencoder	High intelligibility score, fully integrated into cochlear implant signal processors	[238]
Voice activity detection in noise	Adaptive context attention model	Computationally improved speech–noise separation	[239]
Active noise cancellation with microphone arrays	Two sets of MEMS resonant microphone arrays; deep learning-based noise cancellation	Effective noise cancellation for automatic speech recognition tasks	[240]
Google Home acoustic model enhancement	Microphone array, weighted prediction error algorithm, factored Complex Linear Projection and Grid LSTM	8–28% relative word error rate reduction compared to the existing production system	[241]

Google Home is a popular smart speaker system that processes speech in the cloud. When using Google Home, the acoustics are far from ideal, as the user is usually far away from the device, and a significant amount of environmental noise is recorded as well. As a result, efficient acoustic modeling is critical for Google Home applications [241]. The Google Home includes a two-microphone array. Two channels of speech can be processed, allowing for improved speech quality while also necessitating more computational power. To jointly process multichannel audio data, the processing workflow includes a weighted prediction error algorithm for dereverberation, a factored Complex Linear Projection, and a Grid LSTM. To cover real-life scenarios, the 18k h of training data includes several room, noise type, noise level, and spekaer position simulations. The evaluation was carried out on clean, simulated, and real data, yielding a relative word error rate reduction of 8–28 percent when compared to the existing production system.

6.6. Lessons Learned

We discussed the role of speech technology in Industry 4.0 in this chapter. Furthermore, we demonstrated cutting-edge research results in the field of speech technology in a variety of industrial fields, including healthcare, industrial robots, IoT, and security applications. We discussed the major challenges that researchers face when implementing speech technology in that field. Background noise is still the most significant barrier to the usability and reliability of speech technology.

7. Conclusions

This paper provided an overview of various current infocommunication technology-related solutions that support industry 4.0. Due to the low latency, high availability, and high security requirements of the industrial domains, the paper surveyed various telco-grade solutions, as these aim to satisfy such requirements by their definition.

Since manufacturing is an important part of the industry 4.0 movement, many of the above mentioned requirements are initiated from this domain. This paper pays special attention to communication and interoperability aspects of manufacturing, and since these fundamentally affect system planning, the paper provides an overview of related modeling approaches, as well. A complete chapter is dedicated to system interoperability, another to modeling, and yet another to 5G functions and features that support the desired levels of information flow. Human-in-the-loop is considered in many ways throughout the paper, but as speech is becoming a major interface in industrial applications, issues related to speech technology applications received a complete chapter in this paper as well.

The paper covers broad areas of the converging areas of 5G technologies and industry 4.0, with a brief insight of 6G requirements and—so far—promises. Altogether, it provides a state-of-the-art survey on this honeymoon of 5G/6G and the industry 4.0 movements from engineering, interoperability and integrability, telco-cloud infrastructure and speech application points of view. First, it provides a comprehensive overview on model-driven engineering (MDE) techniques and tools to be used for planning, modeling and designing complex systems. Second, it outlines interoperability and integrability frameworks for cyber-physical system of systems to be applied in multi-level, multi-stakeholder industrial production. Third, it extends the 5G service slicing guarantees with the offerings of telco-clouds, with a comprehensive comparison of traditional and telco-cloud solutions. Fourth, it provides an overview of speech recognition applications in the production area, including security-related issues and handling noisy environments.

In each of the chapters, the paper provides comparative tables and lessons learned sections to highlight the main points of the state-of-the-art and the main achievements in these converging domains.

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References

1. Wang, Y.; Lo, H.P.; Yang, Y. An integrated framework for service quality, customer value, satisfaction: Evidence from China's telecommunication industry. *Inf. Syst. Front.* **2004**, *6*, 325–340. [CrossRef]
2. GSMA. Mobile Telecommunications Security Threat Landscape. White Paper. 2020. Available online: https://www.gsma.com/security/wp-content/uploads/2020/02/2020-SECURITY-THREAT-LANDSCAPE-REPORT-FINAL.pdf (accessed on 26 July 2022).
3. Ayers, M.L. *Telecommunications System Reliability Engineering, Theory, and Practice*; John Wiley & Sons: New York, NY, USA, 2012.
4. Varga, P.; Olaszi, P. LTE core network testing using generated traffic based on models from real-life data. In Proceedings of the 2013 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), Kattankulathur, India, 15–18 December 2013; pp. 1–6. [CrossRef]
5. ITU-R. IMT Vision—Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond. M. 2083-0. 2019. Available online: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf (accessed on 26 July 2022).
6. Sniderman, B.; Mahto, M.; Cotteleer, M.J. *Industry 4.0 and Manufacturing Ecosystems*; Report; Deloitte University Press: Westlake, TX, USA, 2016.
7. Kozma, D.; Varga, P.; Hegedüs, C. Supply Chain Management and Logistics 4.0 - A Study on Arrowhead Framework Integration. In Proceedings of the 2019 8th International Conference on Industrial Technology and Management (ICITM), Cambridge, UK, 2–4 March 2019; pp. 12–16. [CrossRef]
8. Soos, G.; Ficzere, D.; Padovani, R.; Franko, A.; Veress, S.; Varga, P. 5G Networks for Industrial Applications: The Ecosystem of NPNs. In Proceedings of the IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), Hyderabad, India, 13–16 December 2021.
9. Paniagua, C.; Delsing, J. Industrial Frameworks for Internet of Things: A Survey. *IEEE Syst. J.* **2020**, *15* , 1–11. [CrossRef]
10. OMA SpecWorks: Lightweight M2M (LWM2M). 2020. Available online: https://www.omaspecworks.org/what-is-oma-specworks/iot/lightweight-m2m-lwm2m/ (accessed on 29 December 2020).
11. Open Connectivity Foundation: OCF Specifications. 2020. Available online: https://openconnectivity.org/specs (accessed on 29 December 2020).
12. Industrial Data Spaces Association: IDS Reference Architecture Model. 2020. Available online: https://www.internationaldataspaces.org/the-principles/ (accessed on 29 December 2020).
13. Autosar Official Website. 2020. Available online: https://www.autosar.org (accessed on 29 December 2020).
14. BaSys 4.0: Basic System Industry 4.0. 2020. Available online: https://www.basys40.de (accessed on 29 December 2020).
15. Fiware: The oPen Source Platform for Our Smart Digital Future. 2020. Available online: https://www.fiware.org (accessed on 29 December 2020).
16. Varga, P.; Blomstedt, F.; Ferreira, L.L.; Eliasson, J.; Johansson, M.; Delsing, J.; de Soria, I.M. Making System of Systems Interoperable—The Core Components of the Arrowhead Framework. *J. Netw. Comput. Appl.* **2016**, *81*, 85–95. [CrossRef]
17. Delsing, J.; Eliasson, J.; van Deventer, J.; Derhamy, H.; Varga, P. Enabling IoT Automation using Local Clouds. In Proceedings of the 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT), Reston, VA, USA, 12–14 December 2016; pp. 502–507.
18. Hegedus, C.; Varga, P.; Frankó, A. Secure and trusted inter-cloud communications in the arrowhead framework. In Proceedings of the 2018 IEEE Industrial Cyber-Physical Systems (ICPS), Saint Petersburg, Russia, 15–18 May 2018; pp. 755–760. [CrossRef]
19. Eclipse Arrowhead. 2020. Available online: https://projects.eclipse.org/projects/iot.arrowhead (accessed on 29 December 2020).
20. Delsing, J.; Varga, P.; Ferreira, L.; Albano, M.; Puñal Pereira, P.; Eliasson, J.; Carlsson, O.; Derhamy, H. The Arrowhead Framework Architecture: Arrowhead Framework. 2017; pp. 43–88. Available online: https://www.taylorfrancis.com/chapters/edit/10.1201/9781315367897-13/arrowhead-framework-architecture-jerker-delsing-pal-varga-luis-ferreira-michele-albano-pablo-pu (accessed on 26 July 2022). [CrossRef]
21. Derhamy, H.; Eliasson, J.; Delsing, J.; Pereira, P.P.; Varga, P. Translation error handling for multi-protocol SOA systems. In Proceedings of the 2015 IEEE 20th Conference on Emerging Technologies Factory Automation (ETFA), Luxembourg, 8–11 September 2015; pp. 1–8. [CrossRef]
22. Kozma, D.; Soos, G.; Varga, P. Supporting Digital Production, Product Lifecycle and Supply Chain Management in Industry 4.0 by the Arrowhead Framework—A Survey. In Proceedings of the IEEE International Conference on Industrial Informatics (INDIN), Helsinki-Espoo, Finland, 22–25 July 2019.
23. Kozma, D.; Varga, P. Supporting Digital Supply Chains by IoT Frameworks: Collaboration, Control, Combination. *Infocommun. J.* **2020**, *12*, 22–32. [CrossRef]
24. Patel, P.; Cassou, D. Enabling high-level application development for the Internet of Things. *J. Syst. Softw.* **2015**, *103*, 62 – 84. [CrossRef]
25. Hudak, P. Domain Specific Languages. 1998. Available online: http://cs448h.stanford.edu/DSEL-Little.pdf (accessed on 26 July 2022).

26. Selic, B.; Gérard, S. An Introduction to UML Profiles. In *Modeling and Analysis of Real-Time and Embedded Systems with UML and MARTE*; 2014. Available online: https://www.sciencedirect.com/science/article/pii/B978012416619600002X?via%3Dihub (accessed on 26 July 2022). [CrossRef]
27. Dhouib, S.; Cuccuru, A.; Fèvre, F.L.; Li, S.; Maggi, B.; Paez, I.; Rademarcher, A.; Rapin, N.; Tatibouet, J.; Tessier, P.; et al. Papyrus for IoT—A Modeling Solution for IoT. 2016. Available online: https://ido2016.sciencesconf.org/122755/20161108_IoTNokia_vfinal.pdf (accessed on 26 July 2022).
28. Christensen, J. IEC 61499 Architecture, Engineering Methodologies and Software Tools. In *Knowledge and Technology Integration in Production and Services*; Mařík, V., Camarinha-Matos, L., Afsarmanesh, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2002; Volume 101, pp. 221–228. [CrossRef]
29. IEC61499 IMPLEMENTATIONS. Available online: https://www.iec61499.de/tools.htm (accessed on 3 December 2020).
30. Strasser, T.; Rooker, M.; Ebenhofer, G.; Zoitl, A.; Sunder, C.; Valentini, A.; Martel, A. Framework for Distributed Industrial Automation and Control (4DIAC). In Proceedings of the 2008 6th IEEE International Conference on Industrial Informatics, Daejeon, Korea, 13–16 July 2008; pp. 283–288.
31. Eclipse Vorto. 2020. Available online: https://www.eclipse.org/vorto/ (accessed on 3 December 2020).
32. Nguyen, X.; Tran, H.T.; Baraki, H.; Geihs, K. FRASAD: A framework for model-driven IoT Application Development. In Proceedings of the IEEE 2nd World Forum on Internet of Things (WF-IoT), Milan, Italy, 14–16 December 2015; pp. 387–392. [CrossRef]
33. Morin, B.; Harrand, N.; Fleurey, F. Model-Based Software Engineering to Tame the IoT Jungle. *IEEE Softw.* **2017**, *34*, 30–36. [CrossRef]
34. Harrand, N.; Fleurey, F.; Morin, B.; Husa, K.E. ThingML: A Language and Code Generation Framework for Heterogeneous Targets. In Proceedings of the ACM/IEEE 19th International Conference on Model Driven Engineering Languages and Systems, Palais du Grand Large, Saint Malo, Brittany, France, 2–7 October 2016; Association for Computing Machinery: New York, NY, USA, 2016; pp. 125–135. [CrossRef]
35. Vasilevskiy, A.; Morin, B.; Haugen, Ø.; Evensen, P. Agile development of home automation system with ThingML. In Proceedings of the 2016 IEEE 14th International Conference on Industrial Informatics (INDIN), Poitiers, France, 19–21 July 2016; pp. 337–344. [CrossRef]
36. Fleurey, F.; Morin, B. ThingML: A Generative Approach to Engineer Heterogeneous and Distributed Systems. In Proceedings of the 2017 IEEE International Conference on Software Architecture Workshops (ICSAW), Gothenburg, Sweden, 5–7 April 2017; pp. 185–188. [CrossRef]
37. Alves, M.P.; Delicato, F.C.; Pires, P.F. IoTA-MD: A Model-Driven Approach for Applying QoS Attributes in the Development of the IoT Systems. In Proceedings of the Symposium on Applied Computing, Marrakech, Morocco, 4–6 April 2017; Association for Computing Machinery: New York, NY, USA, 2017; pp. 1773–1780. [CrossRef]
38. OMG MDA. 2019. Available online: https://www.omg.org/mda/ (accessed on 3 December 2020).
39. Nepomuceno, T.; Carneiro, T.; Maia, P.H.; Adnan, M.; Nepomuceno, T.; Martin, A. AutoIoT: A framework based on user-driven MDE for generating IoT applications. In Proceedings of the 35th Annual ACM Symposium on Applied Computing, Brno, Czech Republic, 30 March–3 April 2020.
40. MagicDraw. 2009. Available online: https://www.nomagic.com/products/magicdraw (accessed on 30 December 2020).
41. Kulcsár, G.; Koltai, K.; Tanyi, S.; Péceli, B.; Horváth, Á.; Micskei, Z.; Varga, P. From Models to Management and Back: Towards a System-of-Systems Engineering Toolchain. In Proceedings of the NOMS 2020-2020 IEEE/IFIP Network Operations and Management Symposium, Budapest, Hungary, 20–24 April 2020; pp. 1–6. [CrossRef]
42. Unified Modeling Language). Available online: https://www.omg.org/spec/UML/2.5/About-UML/ (accessed on 3 December 2020).
43. Systems Modeling Language. 2005. Available online: https://sysml.org/ (accessed on 20 October 2020).
44. Thramboulidis, K.; Bochalis, P.; Bouloumpasis, J. A framework for MDE of IoT-based manufacturing cyber-physical systems. In Proceedings of the IoT'17, Linz, Austria, 22–25 October 2017.
45. Thramboulidis, K.; Christoulakis, F. UML4IoT-A UML profile to exploit IoT in cyber-physical manufacturing systems. *arXiv* **2015**, arXiv:1512.04894.
46. Costa, B.; Pires, P.F.; Delicato, F.C. Modeling IoT Applications with SysML4IoT. In Proceedings of the 2016 42th Euromicro Conference on Software Engineering and Advanced Applications (SEAA), Limassol, Cyprus, 31 August–2 September 2016; pp. 157–164. [CrossRef]
47. Systems Modeling Language Requirement Diagram. 2005. Available online: https://sysml.org/sysml-faq/what-is-requirement-diagram.html (accessed on 3 December 2020).
48. OMG MARTE. 2019. Available online: https://www.omg.org/spec/MARTE/About-MARTE/ (accessed on 3 December 2020).
49. Eclipse Sirius. 2020. Available online: https://www.eclipse.org/sirius/ (accessed on 3 December 2020).
50. Eclipse Xtext. 2020. Available online: https://www.eclipse.org/Xtext/ (accessed on 3 December 2020).
51. UML Profile for Modeling QoS and FT Characteristics and Mechanisms Specification (QoS&FT). Available online: https://www.omg.org/spec/QFTP/1.1/PDF (accessed on 3 December 2020).
52. PrismTech. Available online: http://www.prismtech.com/ (accessed on 3 December 2020).
53. MicroEJ's Operating System. Available online: https://www.microej.com/product/vee/ (accessed on 3 December 2020).
54. 4diac FORTE. Available online: https://www.eclipse.org/4diac/en_rte.php (accessed on 3 December 2020).

55. Steinberg, D.; Budinsky, F.; Paternostro, M.; Merks, E. *EMF: Eclipse Modeling Framework 2.0*, 2nd ed.; Addison-Wesley Professional: Boston, MA, USA, 2009.
56. Rapin, N. Reactive Property Monitoring of Hybrid Systems with Aggregation. In Proceedings of the RV, Madrid, Spain, 23–30 September 2016.
57. VIATRA. 2009. Available online: https://www.eclipse.org/viatra/ (accessed on 3 December 2020).
58. Wang, X.; Gao, L. Development of Industry 4.0. In *When 5G Meets Industry 4.0*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 43–74.
59. Gandhi, P.; Sharma, R.; Maheshwari, A. Creating Internet of Things for the Benefit of Indian Society. In Proceedings of the 2019 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET), Chennai, India, 21–23 March 2019; pp. 35–40.
60. Ericsson. 5G estimated to reach 1.5 billion subscriptions in 2024—Ericsson Mobility Report. *IEEE Veh. Technol. Mag.* **2018**, *14*, 4–10.
61. Mobile Subscriptions Outlook. Available online: https://www.ericsson.com/en/reports-and-papers/mobility-report/dataforecasts/mobile-subscriptions-outlook (accessed on 8 March 2022).
62. ITU-R. Minimum requirements related to technical performance for IMT-2020 radio interface(s). Report M.2410-0, ITU-R; 2017. Available online: https://www.itu.int/pub/R-REP-M.2410-2017 (accessed on 26 July 2022).
63. Akhtar, M.W.; Hassan, S.A.; Ghaffar, R.; Jung, H.; Garg, S.; Hossain, M.S. The shift to 6G communications: Vision and requirements. *Hum. Centric Comput. Inf. Sci.* **2020**, *10*, 1–27. [CrossRef]
64. Zhao, Y.; Yu, G.; Xu, H. 6G Mobile Communication Network: Vision, Challenges and Key Technologies. *arXiv* **2019**, arXiv:1905.04983.
65. Padhi, P.K.; Charrua-Santos, F. 6G Enabled Industrial Internet of Everything: Towards a Theoretical Framework. *Appl. Syst. Innov.* **2021**, *4*, 11. [CrossRef]
66. Mogyorósi, F.; Revisnyei, P.; Pašić, A.; Papp, Z.; Törös, I.; Varga, P.; Pašić, A. Positioning in 5G and 6G Networks—A Survey. *Sensors* **2022**, *22*, 4757. [CrossRef]
67. Jiang, J. An improved Cyber-Physical Systems architecture for Industry 4.0 smart factories. In Proceedings of the 2017 International Conference on Applied System Innovation (ICASI), Sapporo, Japan, 13–17 May 2017; pp. 918–920. [CrossRef]
68. Schweichhart, K. Reference Architectural Model Industrie 4.0 (RAMI 4.0). An Introduction. 2016; Volume 40. Available online: https://www.plattform-i40 (accessed on 26 July 2022).
69. Tantik, E.; Anderl, R. Potentials of the asset administration shell of Industrie 4.0 for service-oriented business models. *Procedia CIRP* **2017**, *64*, 363–368. [CrossRef]
70. Sharma, R.; Villányi, B. Two-Tier analyzed content filtering based Data Management Architecture in Industry 4.0. In Proceedings of the 2020 IEEE 15th International An improved Cyber-Physical Systems architecture Conference of System of Systems Engineering (SoSE), Budapest, Hungary, 2–4 June 2020; pp. 000543–000548.
71. Cottyn, J.; Van Landeghem, H.; Stockman, K.; Derammelaere, S. A method to align a manufacturing execution system with Lean objectives. *Int. J. Prod. Res.* **2011**, *49*, 4397–4413. [CrossRef]
72. Rolon, M.; Martinez, E. Agent learning in autonomic manufacturing execution systems for enterprise networking. *Comput. Ind. Eng.* **2012**, *63*, 901–925. [CrossRef]
73. Legat, C.; Lamparter, S.; Vogel-Heuser, B. Knowledge-based technologies for future factory engineering and control. In *Service Orientation in Holonic and Multi Agent Manufacturing and Robotics*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 355–374.
74. Zhong, R.Y.; Dai, Q.; Qu, T.; Hu, G.; Huang, G.Q. RFID-enabled real-time manufacturing execution system for mass-customization production. *Robot. Comput. Integr. Manuf.* **2013**, *29*, 283–292. [CrossRef]
75. Lee, S.; Nam, S.J.; Lee, J.K. Real-time data acquisition system and HMI for MES. *J. Mech. Sci. Technol.* **2012**, *26*, 2381–2388. [CrossRef]
76. Yang, Z.; Zhang, P.; Chen, L. RFID-enabled indoor positioning method for a real-time manufacturing execution system using OS-ELM. *Neurocomputing* **2016**, *174*, 121–133. [CrossRef]
77. Morariu, O.; Borangiu, T.; Raileanu, S.; Morariu, C. Redundancy and scalability for virtualized MES systems with programmable infrastructure. *Comput. Ind.* **2016**, *81*, 26–35. [CrossRef]
78. Jiang, P.; Zhang, C.; Leng, J.; Zhang, J. Implementing a WebAPP-based Software Framework for Manufacturing Execution Systems. *IFAC-PapersOnLine* **2015**, *48*, 388–393. [CrossRef]
79. Mónica, R.L.; Christian, B.; Friedrich, M.; Bernd, K.; Urlich, B.; Waldemar, S. Agent-based communication to map and exchange shop floor data between MES and material flow simulation based on the open standard CMSD. *IFAC-PapersOnLine* **2016**, *49*, 1526–1531.
80. Helo, P.; Suorsa, M.; Hao, Y.; Anussornnitisarn, P. Toward a cloud-based manufacturing execution system for distributed manufacturing. *Comput. Ind.* **2014**, *65*, 646–656. [CrossRef]
81. Soete, N.; Claeys, A.; Hoedt, S.; Mahy, B.; Cottyn, J. Towards mixed reality in SCADA applications. *IFAC-PapersOnLine* **2015**, *48*, 2417–2422. [CrossRef]
82. Arica, E.; Powell, D. Status and future of manufacturing execution systems. In Proceedings of the 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, 10–13 December 2017; pp. 2000–2004.

83. Koch, M.T.; Baars, H.; Lasi, H.; Kemper, H.G. Manufacturing Execution Systems and Business Intelligence for Production Environments. In Proceedings of the AMCIS, Lima, Peru, 12–15 August 2010; p. 436.
84. Schmidt, A.; Otto, B.; Österle, H. A functional reference model for manufacturing execution systems in the automotive industry. *Wirtsch. Proc.* **2011**, 302–311.
85. Naedele, M.; Chen, H.M.; Kazman, R.; Cai, Y.; Xiao, L.; Silva, C.V. Manufacturing execution systems: A vision for managing software development. *J. Syst. Softw.* **2015**, *101*, 59–68. [CrossRef]
86. Cupek, R.; Ziebinski, A.; Huczala, L.; Erdogan, H. Agent-based manufacturing execution systems for short-series production scheduling. *Comput. Ind.* **2016**, *82*, 245–258. [CrossRef]
87. Mantravadi, S.; Møller, C. An overview of next-generation manufacturing execution systems: How important is MES for industry 4.0? *Procedia Manuf.* **2019**, *30*, 588–595. [CrossRef]
88. Brecher, C.; Müller, S.; Breitbach, T.; Lohse, W. Viable system model for manufacturing execution systems. *Procedia CIRP* **2013**, *7*, 461–466. [CrossRef]
89. Wang, M.; Dai, Q.; Zhang, X.; Luo, X.; Zhong, R. A RFID-enabled MES for real-time pharmaceutical manufacturing supervision. In Proceedings of the 2010 IEEE International Conference on RFID-Technology and Applications, Guangzhou, China, 17–19 June 2010; pp. 49–53.
90. Kšksal, A.; Tekin, E. Manufacturing execution through e-Factory system. *Procedia CIRP* **2012**, *3*, 591–596. [CrossRef]
91. Unver, H.O. An ISA-95-based manufacturing intelligence system in support of lean initiatives. *Int. J. Adv. Manuf. Technol.* **2013**, *65*, 853–866. [CrossRef]
92. Grauer, M.; Karadgi, S.S.; Metz, D.; Schäfer, W. An Approach for Real-Time Control of Enterprise Processes in Manufacturing using a Rule-Based System. In Proceedings of the MKWI, Göttingen, Germany, 23–25 February 2010; pp. 1511–1522.
93. Trentesaux, D. Distributed control of production systems. *Eng. Appl. Artif. Intell.* **2009**, *22*, 971–978. [CrossRef]
94. Paredes, F.; Herrojo, C.; Mata-Contreras, J.; Moras, M.; Núñez, A.; Ramon, E.; Martín, F. Near-field chipless radio-frequency identification (RFID) sensing and identification system with switching reading. *Sensors* **2018**, *18*, 1148. [CrossRef] [PubMed]
95. Ateya, A.A.; Muthanna, A.; Gudkova, I.; Abuarqoub, A.; Vybornova, A.; Koucheryavy, A. Development of intelligent core network for tactile internet and future smart systems. *J. Sens. Actuator Netw.* **2018**, *7*, 1. [CrossRef]
96. Hassan, N.; Yau, K.L.A.; Wu, C. Edge computing in 5G: A review. *IEEE Access* **2019**, *7*, 127276–127289. [CrossRef]
97. Markakis, E.K.; Karras, K.; Sideris, A.; Alexiou, G.; Pallis, E. Computing, caching, and communication at the edge: The cornerstone for building a versatile 5G ecosystem. *IEEE Commun. Mag.* **2017**, *55*, 152–157. [CrossRef]
98. Zhang, K.; Mao, Y.; Leng, S.; Zhao, Q.; Li, L.; Peng, X.; Pan, L.; Maharjan, S.; Zhang, Y. Energy-efficient offloading for mobile edge computing in 5G heterogeneous networks. *IEEE Access* **2016**, *4*, 5896–5907. [CrossRef]
99. Bastug, E.; Bennis, M.; Debbah, M. Living on the edge: The role of proactive caching in 5G wireless networks. *IEEE Commun. Mag.* **2014**, *52*, 82–89. [CrossRef]
100. Huang, S.C.; Luo, Y.C.; Chen, B.L.; Chung, Y.C.; Chou, J. Application-aware traffic redirection: A mobile edge computing implementation toward future 5G networks. In Proceedings of the 2017 IEEE 7th International Symposium on Cloud and Service Computing (SC2), Kanazawa, Japan, 22–25 November 2017; pp. 17–23.
101. Hsieh, H.C.; Chen, J.L.; Benslimane, A. 5G virtualized multi-access edge computing platform for IoT applications. *J. Netw. Comput. Appl.* **2018**, *115*, 94–102. [CrossRef]
102. Rimal, B.P.; Van, D.P.; Maier, M. Mobile edge computing empowered fiber-wireless access networks in the 5G era. *IEEE Commun. Mag.* **2017**, *55*, 192–200. [CrossRef]
103. Huang, X.; Yu, R.; Kang, J.; He, Y.; Zhang, Y. Exploring mobile edge computing for 5G-enabled software defined vehicular networks. *IEEE Wirel. Commun.* **2017**, *24*, 55–63. [CrossRef]
104. Al Ridhawi, I.; Aloqaily, M.; Kotb, Y.; Al Ridhawi, Y.; Jararweh, Y. A collaborative mobile edge computing and user solution for service composition in 5G systems. *Trans. Emerg. Telecommun. Technol.* **2018**, *29*, e3446. [CrossRef]
105. Tran, T.X.; Hajisami, A.; Pandey, P.; Pompili, D. Collaborative mobile edge computing in 5G networks: New paradigms, scenarios, and challenges. *IEEE Commun. Mag.* **2017**, *55*, 54–61. [CrossRef]
106. Solozabal, R.; Sanchoyerto, A.; Atxutegi, E.; Blanco, B.; Fajardo, J.O.; Liberal, F. Exploitation of mobile edge computing in 5G distributed mission-critical push-to-talk service deployment. *IEEE Access* **2018**, *6*, 37665–37675. [CrossRef]
107. Singh, S.; Chiu, Y.C.; Tsai, Y.H.; Yang, J.S. Mobile edge fog computing in 5G era: Architecture and implementation. In Proceedings of the 2016 International Computer Symposium (ICS), Chiayi, Taiwan, 15–17 December 2016; pp. 731–735.
108. Guo, S.; Shao, S.; Wang, Y.; Yang, H. Cross stratum resources protection in fog-computing-based radio over fiber networks for 5G services. *Opt. Fiber Technol.* **2017**, *37*, 61–68. [CrossRef]
109. Kitanov, S.; Janevski, T. Energy efficiency of Fog Computing and Networking services in 5G networks. In Proceedings of the IEEE EUROCON 2017-17th International Conference on Smart Technologies, Ohrid, Macedonia, 6–8 July 2017; pp. 491–494.
110. Taleb, T.; Dutta, S.; Ksentini, A.; Iqbal, M.; Flinck, H. Mobile edge computing potential in making cities smarter. *IEEE Commun. Mag.* **2017**, *55*, 38–43. [CrossRef]
111. Chen, X.; Pu, L.; Gao, L.; Wu, W.; Wu, D. Exploiting massive D2D collaboration for energy-efficient mobile edge computing. *IEEE Wirel. Commun.* **2017**, *24*, 64–71. [CrossRef]
112. Frankó, A.E.; Varga, P. A Survey on Machine Learning based Smart Maintenance and Quality Control Solutions. *Infocommunications J.* **2021**, *13*, 28–35. [CrossRef]

113. Chen, S.; Ren, B.; Gao, Q.; Kang, S.; Sun, S.; Niu, K. Pattern division multiple access—A novel nonorthogonal multiple access for fifth-generation radio networks. *IEEE Trans. Veh. Technol.* **2016**, *66*, 3185–3196. [CrossRef]
114. Chen, P.; Xu, M.; Bai, B.; Wang, J. Design and performance of polar codes for 5G communication under high mobility scenarios. In Proceedings of the 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, Australia, 4–7 June 2017; pp. 1–5.
115. Gamage, H.; Rajatheva, N.; Latva-Aho, M. Channel coding for enhanced mobile broadband communication in 5G systems. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, 12–15 June 2017; pp. 1–6.
116. Ferreira, J.S.; Rodrigues, H.D.; Gonzalez, A.A.; Nimr, A.; Matthe, M.; Zhang, D.; Mendes, L.L.; Fettweis, G. GFDM frame design for 5G application scenarios. *J. Commun. Inf. Syst.* **2017**, *32*. [CrossRef]
117. IEEE 5G and Beyond Technology Roadmap White Paper. Technical Report; 2017. Available online: https://futurenetworks.ieee.org/images/files/pdf/ieee-5g-roadmap-white-paper.pdf (accessed on 26 July 2022).
118. Li, S.; Da Xu, L.; Zhao, S. 5G Internet of Things: A survey. *J. Ind. Inf. Integr.* **2018**, *10*, 1–9. [CrossRef]
119. Li, S.; Da Xu, L.; Zhao, S. The internet of things: A survey. *Inf. Syst. Front.* **2015**, *17*, 243–259. [CrossRef]
120. Yang, X.; Wang, X.; Zhang, J. Compressed sensing based ACK feedback for grant-free uplink data transmission in 5G mMTC. In Proceedings of the 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Valencia, Spain, 4–8 September 2016; pp. 1–5.
121. Mahmood, N.H.; Pratas, N.; Jacobsen, T.; Mogensen, P. On the performance of one stage massive random access protocols in 5G systems. In Proceedings of the 2016 9th International Symposium on Turbo Codes and Iterative Information Processing (ISTC), Brest, France, 5–9 September 2016; pp. 340–344.
122. Cao, J.; Ma, M.; Li, H.; Fu, Y.; Liu, X. EGHR: Efficient group-based handover authentication protocols for mMTC in 5G wireless networks. *J. Netw. Comput. Appl.* **2018**, *102*, 1–16. [CrossRef]
123. Sharma, R.; Sairam, A.S.; Yadav, A.; Sikora, A. Tunable synchronization in duty-cycled wireless sensor networks. In Proceedings of the 2016 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), Bangalore, India, 6–9 November 2016; pp. 1–6.
124. Chataut, R.; Akl, R. Massive MIMO Systems for 5G and beyond Networks—Overview, Recent Trends, Challenges, and Future Research Direction. *Sensors* **2020**, *20*, 2753. [CrossRef] [PubMed]
125. Baghous, J. 5G system throughput performance evaluation using Massive-MIMO technology with Cluster Delay Line channel model and non-line of sight scenarios. *Infocommun. J.* **2021**, *13*, 40–45. [CrossRef]
126. Kashima, T.; Qiu, J.; Shen, H.; Tang, C.; Tian, T.; Wang, X.; Hou, X.; Jiang, H.; Benjebbour, A.; Saito, Y.; et al. Large scale massive MIMO field trial for 5G mobile communications system. In Proceedings of the 2016 International Symposium on Antennas and Propagation (ISAP), Okinawa, Japan, 24–28 October 2016; pp. 602–603.
127. Fettweis, G.P. The tactile internet: Applications and challenges. *IEEE Veh. Technol. Mag.* **2014**, *9*, 64–70. [CrossRef]
128. Saur, S.; Centenaro, M. Radio access protocols with multi-user detection for URLLC in 5G. In Proceedings of the European Wireless 2017: 23th European Wireless Conference, VDE, Dresden, Germany, 17–19 May 2017; pp. 1–6.
129. Li, C.P.; Jiang, J.; Chen, W.; Ji, T.; Smee, J. 5G ultra-reliable and low-latency systems design. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, 12–15 June 2017; pp. 1–5.
130. Raza, M.; Hussain, S.; Le-Minh, H.; Aslam, N. Novel MAC layer proposal for URLLC in industrial wireless sensor networks. *ZTE Commun.* **2020**, *15*, 50–59.
131. Sharma, R.; Doohan, N.V.; Tokekar, S. A virtual infrastructure using tides for data dissemination in wireless sensor networks for mobile sinks. In Proceedings of the 2015 International Conference on Industrial Instrumentation and Control (ICIC), Pune, India, 28–30 May 2015; pp. 997–1002.
132. Hamamreh, J.M.; Basar, E.; Arslan, H. OFDM-subcarrier index selection for enhancing security and reliability of 5G URLLC services. *IEEE Access* **2017**, *5*, 25863–25875.
133. Realini, C.E.; Marcos, B. Active and intelligent packaging systems for a modern society. *Meat Sci.* **2014**, *98*, 404–419. [CrossRef] [PubMed]
134. Pereira de Abreu, D.; Cruz, J.M.; Paseiro Losada, P. Active and intelligent packaging for the food industry. *Food Rev. Int.* **2012**, *28*, 146–187.
135. Kalpana, S.; Priyadarshini, S.; Leena, M.M.; Moses, J.; Anandharamakrishnan, C. Intelligent packaging: Trends and applications in food systems. *Trends Food Sci. Technol.* **2019**, *93*, 145–157.
136. Müller, P.; Schmid, M. Intelligent packaging in the food sector: A brief overview. *Foods* **2019**, *8*, 16. [CrossRef]
137. Xu, X. Machine Tool 4.0 for the new era of manufacturing. *Int. J. Adv. Manuf. Technol.* **2017**, *92*, 1893–1900. [CrossRef]
138. Liu, W.; Kong, C.; Niu, Q.; Jiang, J.; Zhou, X. A method of NC machine tools intelligent monitoring system in smart factories. *Robot. Comput. Integr. Manuf.* **2020**, *61*, 101842. [CrossRef]
139. Liu, C.; Vengayil, H.; Lu, Y.; Xu, X. A cyber-physical machine tools platform using OPC UA and MTConnect. *J. Manuf. Syst.* **2019**, *51*, 61–74. [CrossRef]
140. Huang, J.; Chen, Q.; Jiang, H.; Zou, B.; Li, L.; Liu, J.; Yu, H. A survey of design methods for material extrusion polymer 3D printing. *Virtual Phys. Prototyp.* **2020**, *15*, 148–162. [CrossRef]
141. Reddy, L.V.K.; Prakash, K.J. A Review on 4D Printing—The Next Industrial Revolution. In *Emerging Trends in Mechanical Engineering*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 325–331.

142. Zhang, Z.; Demir, K.G.; Gu, G.X. Developments in 4D-printing: A review on current smart materials, technologies, and applications. *Int. J. Smart Nano Mater.* **2019**, *10*, 205–224. [CrossRef]
143. González, I.; Calderón, A.J.; Figueiredo, J.; Sousa, J. A literature survey on open platform communications (OPC) applied to advanced industrial environments. *Electronics* **2019**, *8*, 510. [CrossRef]
144. Killi, B.P.R.; Rao, S.V. Controller placement in software defined networks: A comprehensive survey. *Comput. Netw.* **2019**, *163*, 106883. [CrossRef]
145. De Melo, P.F.S.; Godoy, E.P. Controller Interface for Industry 4.0 based on RAMI 4.0 and OPC UA. In Proceedings of the 2019 II Workshop on Metrology for Industry 4.0 and IoT (MetroInd4. 0&IoT), Naples, Italy, 4–6 June 2019; pp. 229–234.
146. Quincozes, S.E.; Soares, A.A.; Oliveira, W.; Cordeiro, E.B.; Lima, R.A.; Muchaluat-Saade, D.C.; Ferreira, V.C.; Lopes, Y.; Vieira, J.L.; Uchôa, L.M.; et al. Survey and Comparison of SDN Controllers for Teleprotection and Control Power Systems. In Proceedings of the LANOMS, Rio de Janeiro, Brazil, 25–27 September 2019.
147. Schultmann, F.; Zumkeller, M.; Rentz, O. Modeling reverse logistic tasks within closed-loop supply chains: An example from the automotive industry. *Eur. J. Oper. Res.* **2006**, *171*, 1033–1050. [CrossRef]
148. Stindt, D.; Sahamie, R. Review of research on closed loop supply chain management in the process industry. *Flex. Serv. Manuf. J.* **2014**, *26*, 268–293. [CrossRef]
149. Bhatia, M.S.; Jakhar, S.K.; Dora, M. Analysis of Barriers to Closed-Loop Supply Chain: A Case of the Indian Automotive Industry. *IEEE Trans. Eng. Manag.* **2020**, *69*, 1999–2013. [CrossRef]
150. Qin, S.J. Survey on data-driven industrial process monitoring and diagnosis. *Annu. Rev. Control* **2012**, *36*, 220–234. [CrossRef]
151. Pickard, M.; Grecu, I.; Grecu, G. Sustainable smart manufacturing in Industry 4.0: Real-time resource planning, process monitoring, and production control. *Econ. Manag. Financ. Mark.* **2019**, *14*, 30–36.
152. Wu, D.; Li, L.; Zhao, X.; Peng, Y.; Yang, P.; Peng, X. Anaerobic digestion: A review on process monitoring. *Renew. Sustain. Energy Rev.* **2019**, *103*, 1–12. [CrossRef]
153. Reis, M.S.; Gins, G. Industrial process monitoring in the big data/industry 4.0 era: From detection, to diagnosis, to prognosis. *Processes* **2017**, *5*, 35. [CrossRef]
154. Phindela, B. The Benefits of Asset Management in Improving Manufacturing Performance in an Explosives Manufacturing Plant. Ph.D. Thesis, University of Johannesburg, Johannesburg, South Africa, 2017.
155. Al-Gumaei, K.; Schuba, K.; Friesen, A.; Heymann, S.; Pieper, C.; Pethig, F.; Schriegel, S. A survey of internet of things and big data integrated solutions for industrie 4.0. In Proceedings of the 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), Torino, Italy, 4–7 September 2018; Volume 1, pp. 1417–1424.
156. de Leeuw, V. Plant Asset Management Best Practices for the Process Industries In *ARC Best Practices*; ARC: Dedham, MA, USA, 2007.
157. Sanchez, M.; Exposito, E.; Aguilar, J. Industry 4.0: Survey from a system integration perspective. *Int. J. Comput. Integr. Manuf.* **2020**, *33*, 1017–1041. [CrossRef]
158. Souza, M.L.H.; da Costa, C.A.; de Oliveira Ramos, G.; da Rosa Righi, R. A survey on decision-making based on system reliability in the context of Industry 4.0. *J. Manuf. Syst.* **2020**, *56*, 133–156. [CrossRef]
159. Ravidas, S.; Lekidis, A.; Paci, F.; Zannone, N. Access control in Internet-of-Things: A survey. *J. Netw. Comput. Appl.* **2019**, *144*, 79–101. [CrossRef]
160. Li, J.; Li, Z.; Chen, F.; Bicchi, A.; Sun, Y.; Fukuda, T. Combined sensing, cognition, learning, and control for developing future neuro-robotics systems: A survey. *IEEE Trans. Cogn. Dev. Syst.* **2019**, *11*, 148–161.
161. Rubio, J.E.; Alcaraz, C.; Roman, R.; Lopez, J. Current cyber-defense trends in industrial control systems. *Comput. Secur.* **2019**, *87*, 101561. [CrossRef]
162. Wang, Z.; Bian, Y.; Shladover, S.E.; Wu, G.; Li, S.E.; Barth, M.J. A survey on cooperative longitudinal motion control of multiple connected and automated vehicles. *IEEE Intell. Transp. Syst. Mag.* **2020**, *12*, 4–24. [CrossRef]
163. Raza, S.; Wang, S.; Ahmed, M.; Anwar, M.R. A survey on vehicular edge computing: Architecture, applications, technical issues, and future directions. *Wirel. Commun. Mob. Comput.* **2019**, *2019*, 3159762. [CrossRef]
164. Ho, T.M.; Tran, T.D.; Nguyen, T.T.; Kazmi, S.; Le, L.B.; Hong, C.S.; Hanzo, L. Next-generation Wireless Solutions for the Smart Factory, Smart Vehicles, the Smart Grid and Smart Cities. *arXiv* **2019**, arXiv:1907.10102.
165. Schellenberger, C.; Zimmermann, M.; Schotten, H.D. Wireless communication for modular production facilities. *arXiv* **2018**, arXiv:1804.08273.
166. Zhang, Y. Short-Term Traffic Flow Prediction Methods: A Survey. *Proc. J. Phys. Conf. Ser.* **2020**, *1486*, 052018. [CrossRef]
167. Głabowski, M.; Hanczewski, S.; Stasiak, M.; Weissenberg, M. Zwierzykowski, P.; Bai, V. Traffic Modeling for Industrial Internet of Things (IIoT) Networks. In Proceedings of the International Conference on Image Processing and Communications, Bydgoszcz, Poland, 11–13 September 2019; Springer: Berlin/Heidelberg, Germany, 2019; pp. 264–271.
168. Nauman, A.; Qadri, Y.A.; Amjad, M.; Zikria, Y.B.; Afzal, M.K.; Kim, S.W. Multimedia Internet of Things: A comprehensive survey. *IEEE Access* **2020**, *8*, 8202–8250. [CrossRef]
169. Gihleb, R.; Giuntella, O.; Stella, L.; Wang, T. Industrial Robots, Workers' Safety, and Health. *Labour Econ.* **2020**, *78*, 102205. [CrossRef]

170. Authier, S.; Abernathy, M.M.; Correll, K.; Chui, R.W.; Dalton, J.; Foley, C.M.; Friedrichs, G.S.; Koerner, J.E.; Kallman, M.J.; Pannirselvam, M.; et al. An Industry Survey With Focus on Cardiovascular Safety Pharmacology Study Design and Data Interpretation. *Int. J. Toxicol.* **2020**, *39*, 274–293. [CrossRef] [PubMed]
171. de Souza Cardoso, L.F.; Mariano, F.C.M.Q.; Zorzal, E.R. A survey of industrial augmented reality. *Comput. Ind. Eng.* **2020**, *139*, 106159. [CrossRef]
172. El Jamiy, F.; Marsh, R. Survey on depth perception in head mounted displays: Distance estimation in virtual reality, augmented reality, and mixed reality. *IET Image Process.* **2019**, *13*, 707–712. [CrossRef]
173. Li, H.; Gupta, A.; Zhang, J.; Flor, N. Who will use augmented reality? An integrated approach based on text analytics and field survey. *Eur. J. Oper. Res.* **2020**, *281*, 502–516. [CrossRef]
174. Gupta, S.; Chaudhary, R.; Gupta, S.; Kaur, A.; Mantri, A. A Survey on Tracking Techniques in Augmented Reality based Application. In Proceedings of the 2019 Fifth International Conference on Image Information Processing (ICIIP), Shimla, India, 15–17 November 2019; pp. 215–220.
175. Lins, R.G.; Givigi, S.N. Cooperative Robotics and Machine Learning for Smart Manufacturing: Platform Design and Trends Within the Context of Industrial Internet of Things. *IEEE Access* **2021**, *9*, 95444–95455. [CrossRef]
176. Zhiqun, X.; Duan, C.; Zhiyuan, H.; Qunying, S. Emerging of telco cloud. *China Commun.* **2013**, *10*, 79–85. [CrossRef]
177. Varga, P.; Peto, J.; Franko, A.; Balla, D.; Haja, D.; Janky, F.; Soos, G.; Ficzere, D.; Maliosz, M.; Toka, L. 5g support for industrial iot applications–challenges, solutions, and research gaps. *Sensors* **2020**, *20*, 828.
178. Barakabitze, A.A.; Ahmad, A.; Mijumbi, R.; Hines, A. 5G network slicing using SDN and NFV: A survey of taxonomy, architectures and future challenges. *Comput. Netw.* **2020**, *167*, 106984. [CrossRef]
179. Ordonez-Lucena, J.; Ameigeiras, P.; Lopez, D.; Ramos-Munoz, J.J.; Lorca, J.; Folgueira, J. Network Slicing for 5G with SDN/NFV: Concepts, Architectures, and Challenges. *IEEE Commun. Mag.* **2017**, *55*, 80–87. [CrossRef]
180. Yousaf, F.Z.; Bredel, M.; Schaller, S.; Schneider, F. NFV and SDN—Key Technology Enablers for 5G Networks. *IEEE J. Sel. Areas Commun.* **2017**, *35*, 2468–2478. [CrossRef]
181. Mebarkia, K.; Zsóka, Z. QoS Impacts of Slice Traffic Limitation. *Infocommunications J. Publ. Sci. Assoc. Infocommunications (HTE)* **2021**, *13*, 24–32.
182. Suthar, P.; Stolic, M. Carrier grade Telco-Cloud. In Proceedings of the 2015 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob), Bandung, Indonesia, 27–29 August 2015; pp. 101–107.
183. Járó, G.; Hilt, A.; Nagy, L.; Tündik, M.Á.; Varga, J. Evolution towards Telco-Cloud: Reflections on Dimensioning, Availability and Operability. In Proceedings of the 2019 42nd International Conference on Telecommunications and Signal Processing (TSP), Budapest, Hungary, 1–3 July 2019; pp. 1–8.
184. Sharma, R.; Villányi, B. Insights from a high-performance Open-Communication Framework for advanced industrial networks. In Proceedings of the 2021 IEEE 21st International Symposium on Computational Intelligence and Informatics (CINTI), Budapest, Hungary, 18–20 November 2021; pp. 000253–000258.
185. Reimagining the End-to-End Mobile Network in the 5G Era. 2019. Available online: https://www.cisco.com/c/dam/en/us/products/collateral/cloud-systems-management/elastic-services-controller-esc/reimagining-mobile-network-white-paper.pdf (accessed on 7 January 2021).
186. A New Model for the Future Network Architecture. 2017. Available online: https://www.ericsson.com/en/news/2017/6/future-network-architecture (accessed on 7 January 2021).
187. Telco Cloud Transformation in the 5G Era. Available online: https://www.juniper.net/us/en/solutions/telco-cloud-transformation/ (accessed on 7 January 2021).
188. Dell EMC and the 5G Network Transformation. 2019. Available online: https://www.delltechnologies.com/en-us/blog/dell-emc-5g-network-transformation/ (accessed on 7 January 2021).
189. Cloud Native for Telco: Making IT Technology Feasible at the Network Edge. 2020. Available online: https://telecoms.com/intelligence/cloud-native-for-telco-making-it-technology-feasible-at-the-network-edge/ (accessed on 7 January 2021).
190. VMware Sees Opportunity as Operators Move from Virtualization to Cloud-Native 5G. 2020. Available online: https://www.rcrwireless.com/20200901/5g/vmware-sees-opportunity-as-operators-move-to-cloud-native-5g (accessed on 7 January 2021).
191. IBM is Building a Telco Cloud 5G Ecosystem Focused on Enterprise Enablement. 2020. Available online: https://www.rcrwireless.com/20201110/5g/ibm-is-building-a-telco-cloud-5g-ecosystem-focused-on-enterprise (accessed on 7 January 2021).
192. Telco Cloud Architecture. 2020. Available online: https://networkinterview.com/telco-cloud-architecture/ (accessed on 7 January 2021).
193. Shariat, M.; Bulakci, Ö.; De Domenico, A.; Mannweiler, C.; Gramaglia, M.; Wei, Q.; Gopalasingham, A.; Pateromichelakis, E.; Moggio, F.; Tsolkas, D.; et al. A flexible network architecture for 5G systems. *Wirel. Commun. Mob. Comput.* **2019**, *2019*, 5264012. [CrossRef]
194. 5G Network Slicing Using SDN and NFV: A Survey of Taxonomy, Architectures and Future Challenges. 2020. Available online: https://www.sciencedirect.com/science/article/pii/S1389128619304773#bib0157 (accessed on 7 January 2021).
195. The Modern Telco Network: Defining The Telco Cloud. 2016. Available online: https://www2.slideshare.net/MarcoRodrigues62/the-modern-telco-network-defining-the-telco-cloud/13 (accessed on 7 January 2021).

196. Krzywda, J.; Tärneberg, W.; Östberg, P.O.; Kihl, M.; Elmroth, E. Telco clouds: Modelling and simulation. In Proceedings of the The 5th International Conference on Cloud Computing and Services Science (CLOSER 2015), Lisbon, Portugal, 20–22 May 2015; pp. 597–609.
197. Vilalta, R.; López, V.; Giorgetti, A.; Peng, S.; Orsini, V.; Velasco, L.; Serral-Gracia, R.; Morris, D.; De Fina, S.; Cugini, F.; et al. TelcoFog: A unified flexible fog and cloud computing architecture for 5G networks. *IEEE Commun. Mag.* **2017**, *55*, 36–43.
198. Bosch, P.; Duminuco, A.; Pianese, F.; Wood, T.L. Telco clouds and virtual telco: Consolidation, convergence, and beyond. In Proceedings of the 12th IFIP/IEEE International Symposium on Integrated Network Management (IM 2011) and Workshops, Dublin, Ireland, 23–27 May 2011; pp. 982–988.
199. Taleb, T. Toward carrier cloud: Potential, challenges, and solutions. *IEEE Wirel. Commun.* **2014**, *21*, 80–91. [CrossRef]
200. Soares, J.; Gonçalves, C.; Parreira, B.; Tavares, P.; Carapinha, J.; Barraca, J.P.; Aguiar, R.L.; Sargento, S. Toward a telco cloud environment for service functions. *IEEE Commun. Mag.* **2015**, *53*, 98–106. [CrossRef]
201. Telco Cloud vs. IT Cloud. 2020. Available online: https://networkinterview.com/telco-cloud-vs-it-cloud/ (accessed on 7 January 2021).
202. Németh, L.; Bíró, J. A holistic view of telco clouds. In Proceedings of the World Telecommunications Congress, WTC'2012, Miyazaki, Japan, 5–6 March 2012.
203. Ananthanarayanan, G.; Bahl, P.; Bodík, P.; Chintalapudi, K.; Philipose, M.; Ravindranath, L.; Sinha, S. Real-time video analytics: The killer app for edge computing. *computer*, **2017**, *50*, 58–67. [CrossRef]
204. Abbas, N.; Zhang, Y.; Taherkordi, A.; Skeie, T. Mobile edge computing: A survey. *IEEE Internet Things J.* **2017**, *5*, 450–465. [CrossRef]
205. Pritchard, C.; Beheshti, Y.; Sepahi, M. Mobile Edge Computing: Architecture, Use-Cases, Applications. 2020. Available online: https://hal.archives-uvertes.fr/hal-02612631 (accessed on 26 July 2022).
206. Vick, A.; Vonásek, V.; Pěnička, R.; Krüger, J. Robot control as a service—Towards cloud-based motion planning and control for industrial robots. In Proceedings of the 2015 10th International Workshop on Robot Motion and Control (RoMoCo), Poznań, Poland, 8–10 July 2015; pp. 33–39.
207. Wang, L.; Liu, M.; Meng, M.Q.H. Real-time multisensor data retrieval for cloud robotic systems. *IEEE Trans. Autom. Sci. Eng.* **2015**, *12*, 507–518. [CrossRef]
208. Fazio, M.; Celesti, A.; Puliafito, A.; Villari, M. Big data storage in the cloud for smart environment monitoring. *Procedia Comput. Sci.* **2015**, *52*, 500–506. [CrossRef]
209. Costa, C.; Zeinalipour-Yazti, D. Telco Big Data Research and Open Problems. In Proceedings of the 2019 IEEE 35th International Conference on Data Engineering (ICDE), Macao, 8–11 April 2019; pp. 2056–2059. [CrossRef]
210. Li, J.Q.; Yu, F.R.; Deng, G.; Luo, C.; Ming, Z.; Yan, Q. Industrial internet: A survey on the enabling technologies, applications, and challenges. *IEEE Commun. Surv. Tutorials* **2017**, *19*, 1504–1526. [CrossRef]
211. Khan, F.Q.; Ishaq, M.; Khan, A.I.; Soubani, B. Adapting Cloud Computing in Higher Education. *Int. J. Sci. Eng. Res.* **2014**, *5*, 823–830.
212. Dang, L.M.; Piran, M.; Han, D.; Min, K.; Moon, H. A survey on internet of things and cloud computing for healthcare. *Electronics* **2019**, *8*, 768. [CrossRef]
213. Thuemmler, C.; Paulin, A.; Lim, A.K. Determinants of next generation e-health network and architecture specifications. In Proceedings of the 2016 IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom), Munich, Germany, 14–17 September 2016; pp. 1–6.
214. Hossain, M.S.; Muhammad, G. Emotion-aware connected healthcare big data towards 5G. *IEEE Internet Things J.* **2017**, *5*, 2399–2406. [CrossRef]
215. Alsharif, M.H.; Nordin, R. Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells. *Telecommun. Syst.* **2017**, *64*, 617–637. [CrossRef]
216. Kumah-Crystal, Y.A.; Pirtle, C.J.; Whyte, H.M.; Goode, E.S.; Anders, S.H.; Lehmann, C.U. Electronic health record interactions through voice: A review. *Appl. Clin. Inform.* **2018**, *9*, 541. [CrossRef] [PubMed]
217. Newman, N. The Future of Voice and the Implications for News. 2018. Available online: https://ora.ox.ac.uk/objects/uuid:c1ab8cef-79d4-4be6-8c8b-3a490483741b (accessed on 26 July 2022).
218. Chen, M.; Yang, J.; Hao, Y.; Mao, S.; Hwang, K. A 5G cognitive system for healthcare. *Big Data Cogn. Comput.* **2017**, *1*, 2. [CrossRef]
219. Adeel, A.; Ahmad, J.; Hussain, A. Real-time lightweight chaotic encryption for 5g iot enabled lip-reading driven secure hearing-aid. *arXiv* **2018**, arXiv:1809.04966.
220. Ilievski, A.; Dojchinovski, D.; Gusev, M. Interactive Voice Assisted Home Healthcare Systems. In Proceedings of the 9th Balkan Conference on Informatics, Sofia, Bulgaria, 26–28 September 2019; pp. 1–5.
221. Villani, V.; Pini, F.; Leali, F.; Secchi, C. Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics* **2018**, *55*, 248–266. [CrossRef]
222. Du, G.; Chen, M.; Liu, C.; Zhang, B.; Zhang, P. Online robot teaching with natural human–robot interaction. *IEEE Trans. Ind. Electron.* **2018**, *65*, 9571–9581. [CrossRef]
223. Zinchenko, K.; Wu, C.Y.; Song, K.T. A study on speech recognition control for a surgical robot. *IEEE Trans. Ind. Inform.* **2016**, *13*, 607–615. [CrossRef]
224. Rogowski, A. Web-based remote voice control of robotized cells. *Robot. Comput. Integr. Manuf.* **2013**, *29*, 77–89. [CrossRef]

225. Hossain, M.S.; Muhammad, G.; Alamri, A. Smart healthcare monitoring: A voice pathology detection paradigm for smart cities. *Multimed. Syst.* **2019**, *25*, 565–575. [CrossRef]
226. Chern, A.; Lai, Y.H.; Chang, Y.P.; Tsao, Y.; Chang, R.Y.; Chang, H.W. A smartphone-based multi-functional hearing assistive system to facilitate speech recognition in the classroom. *IEEE Access* **2017**, *5*, 10339–10351. [CrossRef]
227. Chiu, P.S.; Chang, J.W.; Lee, M.C.; Chen, C.H.; Lee, D.S. Enabling Intelligent Environment by the Design of Emotionally Aware Virtual Assistant: A Case of Smart Campus. *IEEE Access* **2020**, *8*, 62032–62041. [CrossRef]
228. Ma, Z.; Liu, Y.; Liu, X.; Ma, J.; Li, F. Privacy-preserving outsourced speech recognition for smart IoT devices. *IEEE Internet Things J.* **2019**, *6*, 8406–8420. [CrossRef]
229. Ding, J.; Lin, S.K. Performance improvement of Kinect software development kit–constructed speech recognition using a client–server sensor fusion strategy for smart human–computer interface control applications. *IEEE Access* **2017**, *5*, 4154–4162. [CrossRef]
230. Sheikh, J.A.; Akhter, S.; Parah, S.A.; Bhat, G.M. Blind digital speech watermarking using filter bank multicarrier modulation for 5G and IoT driven networks. *Int. J. Speech Technol.* **2018**, *21*, 715–722. [CrossRef]
231. Mao, J.; Zhu, S.; Xuan, D.; Lin, Q.; Liu, J. Watchdog: Detecting Ultrasonic-based Inaudible Voice Attacks to Smart Home Systems. *IEEE Internet Things J.* **2020**, *26*, 8025–8035. [CrossRef]
232. Tran, V.T.; Tsai, W.H. Speaker Identification in Multi-Talker Overlapping Speech Using Neural Networks. *IEEE Access* **2020**, *8*, 134868–134879. [CrossRef]
233. Xu, J.; Li, S.; Jiang, J.; Dou, Y. A Simplified Speaker Recognition System Based on FPGA Platform. *IEEE Access* **2019**, *8*, 1507–1516. [CrossRef]
234. Kim, G.; Lee, H.; Kim, B.K.; Oh, S.H.; Lee, S.Y. Unpaired speech enhancement by acoustic and adversarial supervision for speech recognition. *IEEE Signal Process. Lett.* **2018**, *26*, 159–163. [CrossRef]
235. Wang, M.; Zhang, E.; Tang, Z. Speech enhancement based on NMF under electric vehicle noise condition. *IEEE Access* **2018**, *6*, 9147–9159. [CrossRef]
236. Jiang, Q.; Chang, F.; Sheng, B. Bearing fault classification based on convolutional neural network in noise environment. *IEEE Access* **2019**, *7*, 69795–69807. [CrossRef]
237. Palla, A.; Fanucci, L.; Sannino, R.; Settin, M. Wearable Speech Enhancement System for Motor Impaired People. In Proceedings of the International Conference on Applications in Electronics Pervading Industry, Environment and Society, Rome, Italy, 15–16 September 2016; Springer: Rome, Italy, 2016; pp. 159–165.
238. Lai, Y.H.; Tsao, Y.; Lu, X.; Chen, F.; Su, Y.T.; Chen, K.C.; Chen, Y.H.; Chen, L.C.; Li, L.P.H.; Lee, C.H. Deep learning–based noise reduction approach to improve speech intelligibility for cochlear implant recipients. *Ear Hear.* **2018**, *39*, 795–809. [CrossRef] [PubMed]
239. Kim, J.; Hahn, M. Voice activity detection using an adaptive context attention model. *IEEE Signal Process. Lett.* **2018**, *25*, 1181–1185. [CrossRef]
240. Liu, H.; Liu, S.; Shkel, A.A.; Kim, E.S. Active Noise Cancellation With MEMS Resonant Microphone Array. *J. Microelectromech. Syst.* **2020**, *29*, 839–845. [CrossRef] [PubMed]
241. Li, B.; Sainath, T.N.; Narayanan, A.; Caroselli, J.; Bacchiani, M.; Misra, A.; Shafran, I.; Sak, H.; Pundak, G.; Chin, K.K.; et al. Acoustic Modeling for Google Home. In Proceedings of the Interspeech, Stockholm, Sweden, 20–24 August 2017; pp. 399–403.