

**TACTILE INTERNET
ENABLED BY
PERVASIVE NETWORKS**

The Internet, which was created to provide resilient and interoperable communication across the globe, evolved to transport a vast amount of content with which to enrich our real-life experience. Today, it provides a depth of information and social sophistication that rivals the real world. The Tactile Internet, the next evolutionary step, will enable remote, real-time physical interaction with real and virtual objects, creating a two-way interactive experience in which boundaries between the real world and virtual world will blur. The implications for society and the applications for specific industries – including Industry X.O, banking and finance, and connected driving – are limitless.

This paper focuses on the technical requirements for the Tactile Internet that will need to be addressed by innovative technologies, foremost the deployment of 5G networks. It provides a general overview of key performance indicators (KPIs), application fields and major technical challenges as well as several suggested measures for modifying the network infrastructure and air interface with legacy and future networks. Challenges associated with planning, building and operating the Tactile Internet are also analyzed and addressed. Finally, an analysis of how the Tactile Internet could support future smart city applications shows that to successfully make such applications a reality CSPs and municipalities need to act now.

The envisioned purpose of the Tactile Internet is to enable the delivery of real-time control and physical (haptic) experiences remotely [2]-[4]. Unlike conventional Internet embodiments, the Tactile Internet provides a medium for remote physical interaction in real time, which requires the exchange of closed-loop information between virtual and/or real objects (i.e., humans, machines, and processes). Ongoing standardization efforts in the working group IEEE P1918.1 define the Tactile Internet as,



A network or network of networks for remotely accessing, perceiving, manipulating or controlling real or virtual objects or processes in perceived real time by humans or machines [5].

In addition to academia, several key industry/public players currently contribute to this standardization working group.

The fifth generation (5G) of mobile communication networks is likely to be one of the most important and necessary technologies for addressing business and other demands in 2020 and beyond. In fact, compared with its previous-generation counterparts, 5G will represent not only an evolution, but also a revolution, in the network domain. It will be a key enabler for the Tactile Internet, providing not only much greater throughput and higher capacity than previous generations of mobile networks, but also much lower latency, ultra-high reliability, and much higher connection density, while still meeting requirements for security, trust, identity and privacy. 5G networks will eventually empower significant socio-economic transformation, helping to build a highly connected society that will achieve improvements in productivity, sustainability, and well-being. 5G has accordingly attracted a great deal of attention from industry, academia, and policy makers globally [1], [2].

TACTILE INTERNET – MOTIVATION & TECHNOLOGY DEEP-DIVE

A. APPLICATION FIELDS OF THE TACTILE INTERNET AND KEY REQUIREMENTS

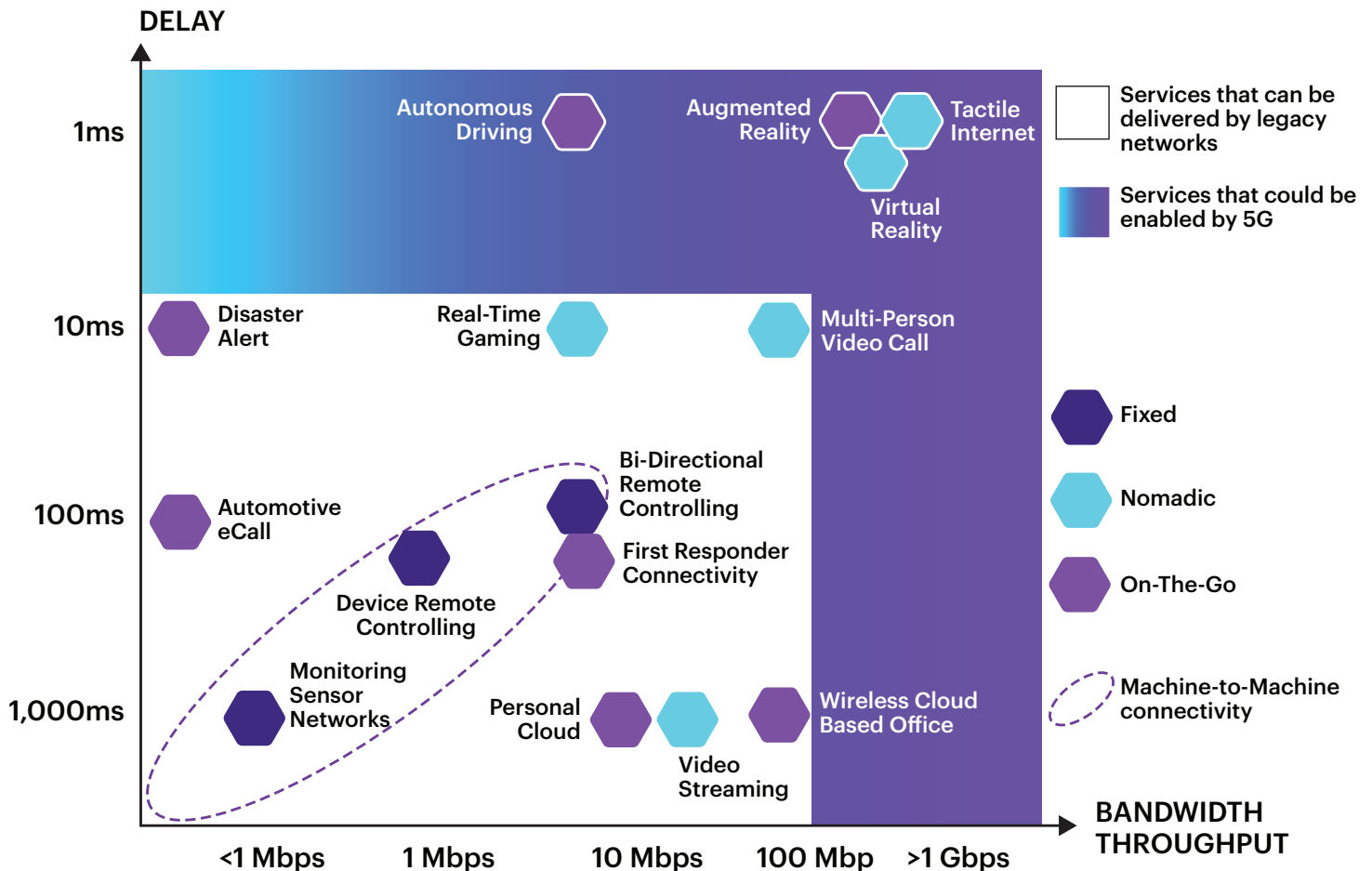
One of the revolutionary potentialities of the Tactile Internet is to remotely deliver not just content, but also skill sets. To do this, however, the Tactile Internet requires ultra-reliable and ultra-responsive network connectivity that can enable the reliability and latency values typically required for physical real-time interaction.

Technically, the Tactile Internet requires building a communication infrastructure that combines low latency, determinism, high availability, resilience and high reliability with a high level of security [2]-[4]. These requirements will not necessarily need to be met simultaneously for all applications, but will need to be met for so-called mission-critical applications, and partially guaranteed for many non-mission critical applications. In order to meet these stringent requirements, the Tactile Internet will need to be associated with cloud computing proximity through IT service environments such as Multi-Access Edge Computing. It will also need to be combined with virtual or augmented reality for sensory and haptic controls, so that it can address local areas with reaction times on the order of a millisecond. When these requirements are met, the Tactile Internet should be able to simultaneously accommodate both mission-critical applications (such as manufacturing, transportation and healthcare) and non-critical applications (such as gaming and edutainment), as follows:

- **Industry X.O:** The traditional manufacturing industry is already being revolutionized by a digital transformation that is accelerated by exponentially growing technologies, such as intelligent robots and sensors [11]. The upcoming fourth industrial revolution (Industry X.O) is based on real-time enabled cyber-physical systems (CPSs), and comes with many key changes in manufacturing, engineering, material usage and supply chain and life cycle management that can lead to flexible and self-organized smart factories. The services and applications provided by cyber-physical system platforms will connect people, objects, and systems to each other. Latency requirements for different applications range from several ms for mechanics, to several ms down to 1ms for machine2machine (M2M), to 1ms for electrics. Also, the sensitivity of rapidly moving devices' control cycles is significantly below 1 ms per sensor, while subsystems rely on a latency of several microseconds [3, 4].

- Automotive:** Fully autonomous driving is expected to change the traffic behavior entirely. By detecting small distances between automated vehicles and potentially safety-critical situations earlier than human drivers, it will enable a significant reduction in road accidents and traffic jams. The time needed for collision avoidance in the vehicle safety applications is below 10 ms. In case a bidirectional data exchange for autonomous driving maneuvers is considered, a latency in the order of a millisecond will likely be needed.
- E-Healthcare:** Using advanced tele-diagnostic tools, medical expertise could be made available anywhere and anytime, regardless of the physician's location. It comes together with stringent requirements on the reliability of wireless connectivity. In addition, an accurate tele-medical treatment can only be realized with haptic feedback, which in turn is possible if the human-to-machine interaction (HMI) can be facilitated in real time [3, 4]. Required in e-health applications for the Tactile Internet, for example, is end-to-end latency of a few milliseconds, together with ultra-high reliability in wireless link connection and data transmission.

Figure 1. Potential innovative applications enabled by Tactile Internet [5].



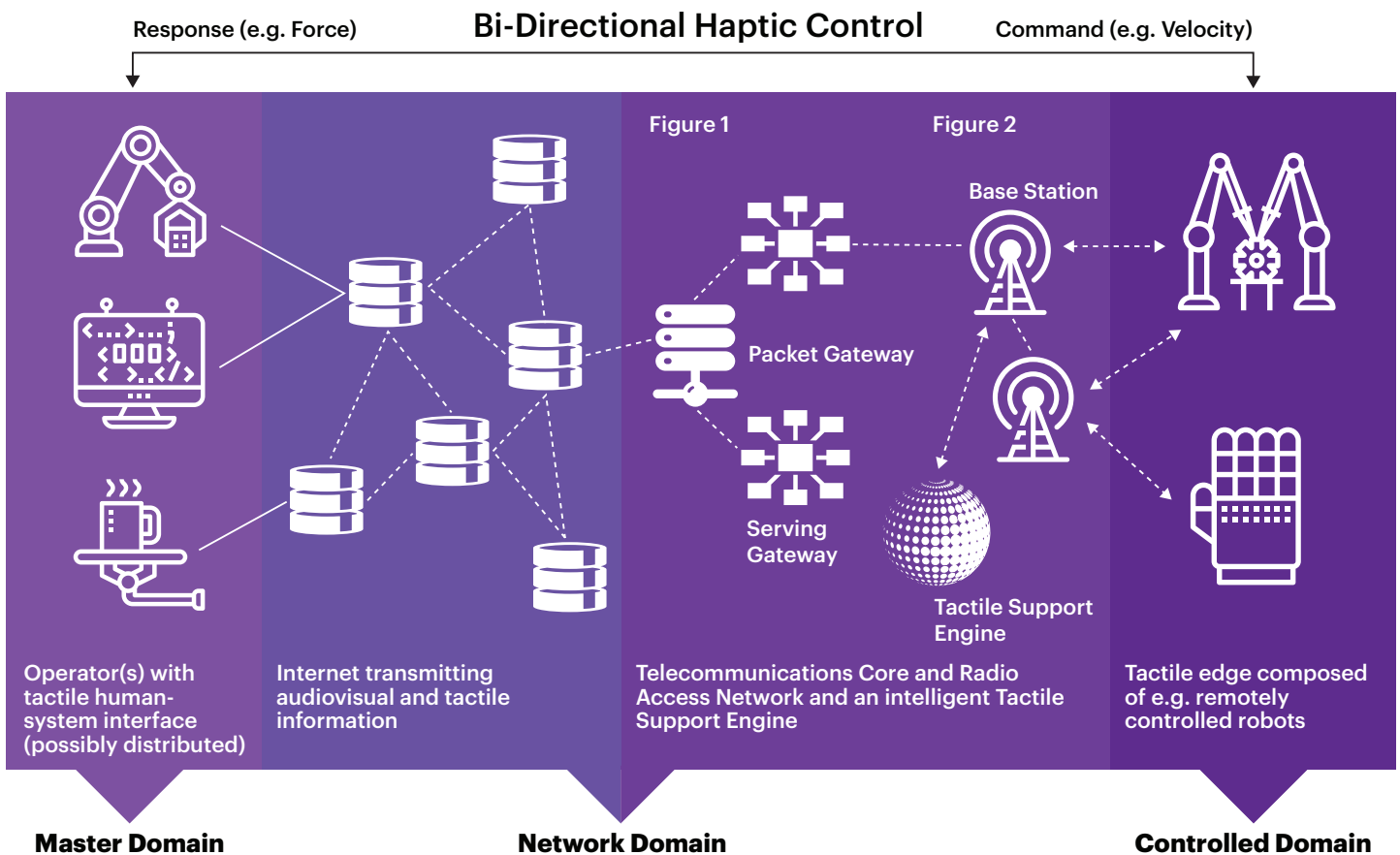
B. TACTILE INTERNET ARCHITECTURE

A 5G-driven communication architecture, composed of the radio access network (RAN) and Core Network (CN), is expected to meet key requirements in realizing the Tactile Internet. As shown in Figure 2, the end-to-end architecture for the Tactile Internet can be split into three distinct domains: a master domain, a network domain, and a controlled domain.

The master domain consists of an operator, i.e., a human or machine, and an operator system interface. This interface is a master robot/controlling device which converts the operator's input to a "tactile internet input" through various coding techniques. If the controlling device is a haptic device, it allows a human to touch, feel, manipulate, or control objects in real or virtual environments. It primarily controls the operation of the controlled domain [13]. In case of a networked control system, the master domain contains a controller, which gives command signals to a sensor/actuator system.

The controlled domain consists of a controlled robot/object, and is controlled directly by the master domain through various command signals for interaction in a remote environment. In case of remote operation with haptic feedback, energy is exchanged between the master and controlled domains, thereby closing a global control loop.

Figure 2: Functional representation of the Tactile Internet architecture.



The network domain provides the medium for bilateral communication between the master and controlled domains, and couples the operator to the remote environment. In case of a human operator, this coupling is kinesthetic.

From a network design point of view, several key challenges need to be addressed by the deployment of 5G networks and beyond:

- **Ultra-responsive network connectivity:** This is especially important for technical systems with haptic interaction or for mission-critical communications, e.g., machine-type communication which enables real-time control and automation of dynamic processes in such areas as industrial automation, manufacturing or traffic management.
- **Carrier-grade access reliability:** Ultra-reliable network connectivity is an important requirement for the Tactile Internet, although specific reliability requirements may differ for various types of applications.
- **Multi-Access Edge Computing:** One potential way to reduce the impact of latency on haptic control is to deploy predictive and interpolative/extrapolative modules closer to the edge of the network in any advanced cloud infrastructure. Such edge-intelligence techniques will play a critical role in making the Tactile Internet a reality. However, multi-access edge computing carries a high cost, which may prohibit its wide deployment [16].
- **Proactive radio resource allocation:** Radio resource management has a direct impact on throughput, latency, reliability, quality of service (QoS) and the performance of higher layers. Due to stringent latency requirements, radio resources must be provided as a priority for mission-critical Tactile Internet applications. In addition, when haptic and other vertical applications need to coexist, 5G networks will require flexible approaches to radio resource management that are capable of providing on-demand functionality.
- **Control feedback loops:** A system supporting Tactile Internet applications requires such loops when signals are exchanged bi-directionally over the network to enable remote control of objects and systems.

- **Core network design:** Network design can help to achieve needed reductions in latency in the core Internet, which is currently variable and largely dictated by queueing delays and geographic routing policies. In the Tactile Internet, even when existing IP security functionalities are sufficient to provide the required security, their placements are too far from the tactile edges to achieve the desired end-to-end latency; novel approaches are thus needed to achieve both adequate security and minimal delay. A thin core network can significantly decrease the protocol overhead and inherently reduce end-to-end latency. Software-defined networking (SDN) and network function virtualization (NFV) paradigms are important here.
- **Network Slicing:** Tactile Internet applications will share the common physical infrastructure of the 5G network with a range of use cases, spanning different vertical industries, not all of which share the same service requirements as the Tactile Internet applications. One way to achieve such flexibility is through network slicing, meaning the use of a connectivity service, based on various customizable logical network (and associated device) functions, to support the requirements of a particular use case. This is possible through the use of NFV and SDN paradigms.
- **Network Co-design:** To make the Tactile Internet application work in real time, it is important to co-design all the technology components involved, such as 5G wireless networks, 5G metro/transport networks and the 5G core network, as well as internet access, architecture and services for managing various data types with manifolds of prioritizations.

C. TECHNICAL FEATURES AND AIR INTERFACE MODIFICATIONS

To meet the challenges imposed by the demanding requirements of Tactile Internet applications, technology innovation is required in many different aspects of network design, from physical layer, protocol, radio resource management and architecture design to hardware. Essentially, technology faces the challenge of providing sufficient network connectivity to enable the latency and reliability required for physical, real-time interaction. While certain Tactile Internet applications, such as cloud robotics and telemedicine, simultaneously require low latency and high reliability, other Tactile Internet applications, such as entertainment and education, rely mainly on low-latency communication. The following discussion envisions several measures that may help to achieve low latency and high reliability in mobile networks.

i. Reducing Latency to the Millisecond Range

Various means are being investigated for reducing the latency of data transmissions in mobile networks. One important approach is to define flexible frame structures and enable versatile numerologies, such as different subcarrier spacings and Transmission Time Intervals (TTIs), to support applications that have distinct requirements. Recent collaborative developments in 3GPP already lead in this direction [7], displaying agreement on different subcarrier spacings and on specific shorter TTIs, e.g., 0.125 ms or below. With the concept of grant-free access and mini-slots (two or more OFDM symbols), it is even possible to significantly drive down latency to sub-ms values [8].

Another latency-related issue is the Hybrid Automatic Repeat Request (HARQ) procedure. In LTE, typically, multiple HARQ retransmissions are allowed, which leads to a very efficient utilization of resources, i.e., high spectral efficiency, due to implicit link adaptation via retransmissions. In contrast, for Tactile Internet applications demanding low latency on the order of milliseconds at maximum, a single retransmission can be allowed in order to keep the latency low. A single retransmission is feasible only if the TTI length is reduced and the number of TTIs between retransmission is lowered as well [6]. Other concepts currently are under development for reducing the HARQ round-trip-times further, such as by using early-feedback techniques. In general, for Tactile Internet applications, it is recommended to exploit other types of diversity than time diversity, and to target a one-shot transmission without retransmissions.

Another source of delays that leads to significant latency is uplink channel access. Here, semi-persistent scheduling can be applied to accelerate the channel access and avoid unnecessary delays. Furthermore, it should be noted that, in addition to the support of low-latency transmissions with minimum processing times, the physical layer architecture should also enable high-throughput transmissions for other applications, such as enhanced Mobile Broadband (eMBB).

Constrained by the speed of light, the distance between communication source and destination should be kept as short as possible to ensure low-latency communications. For instance, if computations are performed in nearby cloud infrastructure directly at the edge of the mobile network instead of in a centralized data center, latency can be minimized [16]. Important prerequisites for edge computing are SDN and NFV. Another potential way to reduce latency is supporting direct communication between devices, instead of using intermediate nodes such as base stations or access points for relaying data transmissions between two devices.

ii. Enhancing Reliability for Selected Applications

High reliability of data transmissions is another key enabler of various Tactile Internet applications, where it needs to be guaranteed that certain transmissions will be performed successfully within a given period of time.

In mobile networks, the degree of reliability is determined by all network components involved, as connectivity interruptions can arise from various effects of these components, such as power loss, electromagnetic interference, hardware failures, and software bugs, just to name a few. Thus, besides the Radio Access Network (RAN), the transport and core networks also need to be designed in such a way that they operate with extremely high availability.

Considering the wireless transmissions in the RAN, a predominant source of failure is the specific wireless channel involved. Receive powers can be insufficiently low due to high path loss or to varying fading components. Moreover, interference from neighboring base stations or terminals can lead to weak signal quality.

A popular and well-known technique to combat such channel-related effects is diversity. By sending and/or receiving multiple versions of the same signal, the signal quality can be enhanced, leading to reduced error rates. Various types of diversity are relevant here, including time, space and frequency diversity:

- Time diversity, as already mentioned above, is exploited in retransmissions to resend data packets in case of transmission errors.

- In spatial diversity, microdiversity, in the form of multiple transmit or receive antennas, helps in combating small-scale fading effects. In addition, macrodiversity is created by using multiple base stations. Existing macrodiversity solutions such as Single Frequency Networks (SFN) or Coordinated Multi-Point (CoMP) have been mainly used for increasing cell-edge throughput and coverage. However, for Tactile Internet applications requiring high reliability, such schemes can help in reducing transmission failures as well. Such macrodiversity setups, where multiple base stations are involved, are also often called multi-connectivity architectures.
- With frequency diversity, transmissions on different carrier frequencies are combined, such as in Carrier Aggregation (CA) or Dual Connectivity (DC). To increase reliability, packet duplication across the radio interfaces is performed, instead of splitting the data, as is done in CA and DC.

In addition, another challenging source of failure is user mobility due to dynamically changing conditions. In LTE, hard handovers are performed when users switch from one cell to another. Even if a handover is successful, an interruption time of approximately 50 ms occurs. In case of handover failures, reestablishment takes significantly longer.

To prevent such interruptions, multi-connectivity at the control plane is currently developed and discussed as well [9]. With multi-connectivity, there are alternative paths to deliver messages, even if a certain link is down due to an ongoing handover. Such make-before-break mechanisms can help in achieving highly reliable connectivity.

Another technique used to further enhance reliability is Network Coding, where information is transmitted in multiple encoded packets across various paths to the destination, enabling improvements in reliability and also latency [12].

Summing up, although diversity is the main enabler of high reliability, fulfilling diverse application requirements requires choosing and adaptively adjusting the number and type of diversity sources used.

TACTILE INTERNET BUSINESS STRATEGY

One of the first questions an operator needs to answer when responding to the new requirements is how to define the right strategy model for enabling Tactile services.

Following the waves of voice, mobility and data services, the advent of IP service created an open market for multiple players to compete on a par with CSPs, and the phenomenon of Over the Top was born. Since then, CSPs have been trying to regain value by embedding distinctive communication features into their product, but with limited success. Competition with OTT players has also proven challenging, due to their agility and the differences introduced by their distinct business model and the unregulated market in which they operate.

With the advent of the Tactile Internet, the IP service layer will become once more profoundly dependent on communication features, and CSPs will have a window of opportunity to define their strategic approach: either they consolidate a commodity-based play, providing connectivity services with enhanced features to the ecosystem, or they become providers of new services, with embedded connectivity.

The multiple scenarios that open up from this simple consideration and their analysis are not within the scope of the present paper. Instead, we focus here on the no-regret moves for capabilities building that will make CSPs able to drive such a decision-making process, navigating successfully the complexity of regulation, competition and co-opetition with ecosystem players.

The key capabilities needed to build Future Networks and enable the Tactile Internet span the full lifecycle of the Network: plan, build, and operate:

- **Plan:** Planning Tactile Services will require smart models for predicting usage patterns and geographical application areas. Additionally, Multi-Access Edge Computing will play an integral part in enabling Tactile Internet Use Cases, while setting additional challenges for an operator of how best to minimize costs and increase ROI. In future Ultra Dense Networks (UDNs) with 1000x more access points [6], the cost per site needs to be lowered to have a sustainable roll-out model. Additionally, the regulatory approval process needs to be much faster and leaner than the current process, which can take up to 18 months for approval of a single cell.

- **Build:** A profitable rollout of the Tactile Internet can be enabled by a range of innovative Digital Network Deployment Solutions (DNDS), including the transformation of field installation and repair through a future Digital Worker approach. Field Force workers will need to become experts in multiple technologies, such as fiber, radio, and Ethernet. Because it will be very hard to find enough skilled workers, CSPs may need to explore digital alternatives. Additionally, new ways of sharing programs and TowerCo Industrialization will have to be implemented in order to enable lower site acquisition costs.
- **Operate:** Operational challenges may be the most impactful of the three. CSPs' Tactile Internet networks will have to understand the services being offered. On top of that, the network will need to be intelligent enough to understand the services being offered and to manage latency. Current CSPs' operations are structured in such a way as to place different groups in charge of different Operational Support System domains (Plan/Build, Assurance, Fault Management), which often do not work together closely and do not rely enough on the complete set of information being produced by the network. That approach will need to change. Given the opportunities for automation made possible by AI, Robotics and Real-Time OSS, CSPs will need to rotate to use resources and analytics to focus on customer experience improvement, proactive actions instead of reactive, and the control and operation of new technologies. To simplify the introduction of these new technologies and obtain their full benefit, this technology transformation will also need to be supported by the transformation of the operating model, process, and people.



INDUSTRY X.O AND TACTILE INTERNET

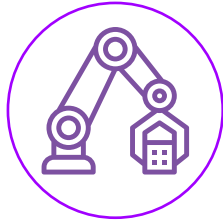
Industry X.O, or the fourth industrial revolution, is the current trend of automation and data exchange in manufacturing technologies. Industry X.O will create what has been called a “smart factory” or a “Factory of the Future” [15]. Within these modular-structured smart factories, cyber-physical systems will monitor physical processes, create a virtual copy of the physical world, and make decentralized decisions. Over different Internet of Things platforms, cyber-physical systems will communicate and cooperate with each other and with humans in real time.

Wireless communications, IoT and cloud computing will represent enabling technologies for many key concepts of Industry X.O, while cross-organizational services will be used by participants in the value chain.

In Industry X.O, there are four design principles which support companies in identifying and implementing Industry X.O scenarios:

- **Interoperable communication:** The ability of machines, devices, sensors and people to connect and communicate with each other via a highly tactile network of communication that ensures quasi-real-time exchange of information and decisions, even if the network resources are shared among mobile virtual network and service operators.
- **Information transparency:** The ability of information systems to create a virtual copy of the physical world by enriching digital plant models with sensor data. This requires the aggregation of raw sensor data into higher-value context information.
- **Technical assistance:** This refers, first, to the ability of assistance systems to support humans by aggregating and visualizing information comprehensibly for making informed decisions and solving urgent problems on short notice, and second, to the ability of cyber-physical systems to physically support humans by conducting a range of tasks that are too unpleasant, exhausting, or unsafe for their human co-workers.
- **Decentralized decisions:** The ability of CPSs to make decisions on their own and to perform their tasks as autonomously as possible. Only in case of exceptions, interferences, or conflicting goals, are tasks delegated to a higher level.

For those principles to yield a valuable outcome, certain technologies and solutions will need to be deployed:



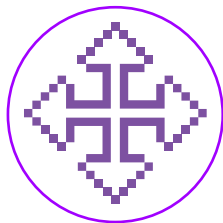
**AUTONOMOUS
ROBOTS**

Automatically self-adjusting, flexible, and cooperative machines will utilize such technologies as RFID tags to address each product in line, while interacting with one another, working safely side by side with humans, and learning from them.



SIMULATION

New simulation technologies will leverage real-time Big Data from production touch points, and the computing power of the Cloud, to mirror the physical world in a virtual model, which can include machines, products, and humans; to efficiently set up machines for each new product line; and to enable rapid testing and therefore added innovation.



**HORIZONTAL AND
VERTICAL SYSTEMS
INTEGRATION**

The collaboration among enterprise departments, functions and partners across value chains will be enhanced because of the enterprise view of data, and networked systems which will enable truly automated value chains.



INDUSTRIAL IOT

Embedded computing sensors in unfinished products will enable them to communicate with the other devices in the production line as necessary, which will facilitate more decentralized decision making and real-time responses.



**AUGMENTED
REALITY**

Augmented reality will extend the physical world and will provide workers with virtual information (in 2D or 3D) overlaying in real-time, in order to enable remote live support and to improve decision making and productivity during assembly, repair and training activities. To avoid the effect of cyber-sickness, as well as for other purposes, AR will combine three major TI challenges: high bandwidth, low E2E latency and high reliability.



CYBER SECURITY

Increased connectivity among devices and use of standard communications protocols in Industry X.0 will increase the need to protect critical industrial systems and manufacturing lines from cyber-security threats.



ADDITIVE
MANUFACTURING

Additive manufacturing methods, such as 3D printing, will be used to add construction advantage to produce small batches of customized products.



THE CLOUD

Industry X.0 will require more data sharing across functions, sites and company boundaries, which will be enabled by Cloud services and their scalability.

Whether it is Industry X.0, or the other use cases mentioned here, the ability to fulfill such technology-driven solutions entails certain challenges that must be resolved to obtain the benefits of those use cases. Among those challenges:

- IT security issues, which are greatly aggravated by the inherent need to open up those previously closed production shops
- Reliability and stability needed for critical machine-to-machine communication (M2M), including very short and stable latency times
- The need to maintain the integrity of production processes
- The need to avoid any IT issues that could cause expensive production outages
- The need to protect industrial intellectual property (contained also in the control files for the industrial automation gear)
- Lack of adequate skill-sets to expedite the march towards the fourth industrial revolution

The role played by 5G service providers in the future, to allow for such tactile, reliable, secure and stable communication ecosystems, is core to the advancement of any Tactile Internet use case.

WHAT DOES IT TAKE TO MAKE THESE USE CASES SUCCESSFUL?

Given the vast number of Tactile Internet applications within the categories outlined, CSPs cannot afford to wait to begin the work for the rollout of the necessary 5G network and fiber infrastructure.

The examples of Tactile Internet applications discussed represent only a small fraction of what is possible. Considering this potential, CSPs need not only to invest in the necessary infrastructure right away, but also to undergo a significant transformation of their existing business model to capitalize on the vast number of opportunities. They need to shift away from a connectivity-based business model and toward an ecosystem of partnerships.

The depth of the transformation required is so significant that it demands immediate action. To support Tactile Internet applications, which require a high degree of reliability, CSP operations need to advance to support complex partnerships, ensure compulsory SLAs, and at the same time, support an elastic operational ecosystem which can cater to a wide range of service agreements.

If the proper investment in 5G and Tactile Internet elements is made, 5G service providers and network owners will be able to lead in such use cases and leverage them for business growth. However, those providers will need to initially invest to develop certain capabilities, including the following:

- **Better Leveraged R&D:** Access to innovation resources at universities and research institutions, combined with the solution for other corporate partners
- **Brand Position:** Positioning as a thought leader in Urban Innovation, Smart City, and Industry X.0 technology
- **Test Bed Environment:** A unique environment to bring together new and existing technologies, pilot solutions in a real-world setting, and speed up the go-to-market proposition
- **Collaboration for Competitive Advantage:** Use each partner's strengths to best solve the problem each cannot achieve unilaterally to put them ahead in the market
- **Customer Engagement:** Active engagement of potential public and private customers throughout solution development
- **Relationship/Partner Development:** Opportunity to work with other industry leaders and built-in go-to-market partners
- **Scalability:** Maintaining a constant eye toward commercialization and ROI beyond the pilot project

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