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Application Scenarios, Research Challenges and Standardization for Tactile Internet

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Information and Communication Systems

OCTOBER 2016

THESSALONIKI – GREECE

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Abstract

This dissertation was written as part of the MSc in Information and Communication Technology (ICT) Systems at the International Hellenic University (IHU).

Mobile data exponential increase in the last years is putting pressure on the network operators, vendors, users as well as on standardization institutions. Competition and collaboration between the previously mentioned players leads to innovations such as IoT (Internet of Things), LTE-Advanced (Long Term Evolution), 5G and the Tactile Internet. Tactile Internet is a new research area that presents very challenging requirements in terms of latency, reliability, security, density of users, devices and links. While it is closely related with the 5G technology as its starting point, it is the nature of Tactile applications that creates an emerging need for standardization. Global players like IEEE (Institute of Electrical and Electronics Engineers), ETSI (European Telecommunications Standards Institute), ITU (International Telecommunication Union) and others are putting significant effort into creating standards and their plan is not to miss the next few years deadline in order to boost the economy.

The goals of this dissertation are to first study the challenges of this new technology and describe the possible solutions for its successful implementation. Secondly, present the potential application scenarios that could be realized ranging from industry automation and transport systems to healthcare, education, gaming and augmented reality. Finally although standardization on Tactile Internet has initiated very recently, the dissertation presents all the efforts made up to date from different standardization bodies on native or related technologies that can materialize Tactile interactions over the Internet.

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Keywords: Tactile Internet, Internet of Things (IoT,) low-latency, high-reliability, mobile edge computing, artificial intelligence

Julian Cakuli

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1 Introduction

Internet has been steadily changing since its appearance about 25 years ago, from a fixed wired infrastructure to a wireless one and from voice-only to video sharing, social networks and real-time applications. Many proposed technology solutions were successfully implemented during this roadmap while many others didn't make it. By successfully meeting the user needs, there has been a paradigm shift towards mobile Internet. This is an infrastructure of Servers, ISPs (Internet Service Provider), networks and user devices that provides access to the internet from a mobile device. Innovations in mobile technologies allow consumers to communicate, create, and share information regardless of their physical location. The industry is moving from content-based to a service-based model and has almost completed its transition. Increased pressure from consumers to use Internet multimedia-rich services has led to efforts to design a standard that embraces all future application demands. Apart from connecting people, the low-cost-driven revolution of Internet of Things (IoT) is emerging as a resource hungry domain which needs to be covered. Billions of people, machines and low-cost devices will create traffic that must be supported by next generation mobile communication (5G). The new technology is not expected to be launched before 2020 due to the preliminary research and tests. As it can be seen from Table 1 5G is expected to improve all metrics of predecessors' standards. By definition it will integrate wireless communications that achieve throughputs in the order or 10 Gb/s, and latency of <1 ms, connecting billions of devices. It could be considered as the next milestone in mobile development since its requirements can cover applications that we cannot even think about. An important part of this domain will be Tactile Internet. Humans' interaction with the surroundings is done through sensation (Picture 1) and the way we perceive the world depends on the five senses.

Picture 1: Human senses (source: www.behance.net)

TACTILE

We get feedback from the environment through signals sent to our brain from sensing receptors. The speed of perception depends om how fast our brain handles the information and what senses are involved in the action-reaction process. For example, a perception- reaction time of 1.5 s is needed for a driver to brake from the moment of getting a dangerous visual stimulation. In order to be naturally perceived, a video must have frame rates of over 100 Hz because our brain doesn't distinguish between frames with less than 10 ms latency. Similarly, for a digital conversation to feel natural, latency must be under 100 ms. Finally, when touch is involved in controlling an object, latency of around 1 ms is required, for example when drawing something with your finger on a painting app on a touch screen. If the responsiveness is over 1 ms then the interaction does not feel real.

Tactile senses will be transmitted remotely adding new dimensions to the Internet. Real–time control with every connected piece of our environment will be possible. Its ultra low latency, together with very high reliability, security and availability will drive the creation of new markets and business opportunities. Supported by 5G and high fidelity fiber networks it will provide an unprecedented human-to-machine interaction in areas such as industry automation, healthcare, transport, smart grids etc. Combined with mobile edge cloud processing artificial intelligence algorithms, Tactile and haptic feedback, it will cover areas with extremely low latency requirements. Existing and new supporting infrastructure needs to be carefully revised towards the goal of having everything connected, anytime and anywhere.

But an important question that arises is if is possible with today's networks to realize Tactile Internet. Although wired connections are close to meeting the strict requirements of Tactile Internet, mobile mission-critical applications cannot be fulfilled by today cellular or WLAN (Wireless Local Area Network) technology. Some characteristics of cellular generations operating in licensed bands are shown in Table 1. 4G performs at quite higher data rates than predecessors and supports applications like High Definition TV, DVB (Digital Video Broadcasting) ,mobile TV, Video calls. However it does not deal effectively with higher capacity, higher data rates, low end to end delay, dense connectivity and low cost. 5G on the other hand will be the main driving force for the new domains of IoT and Tactile Internet. To enable the exponential increase in traffic to be handled in 5G, efficient spectrum allocation is required along with new air interfaces and multiple access schemes. This turns out to millimeter wave optimized frequency, low latency and massive connectivity. Its access technology is expected to use the whole spectrum band from 1 GHz up to 300 GHz with a bandwidth of 60 GHz [68] to support expected data rate of over 10 Gb/s required for ultra-high definition video and virtual reality applications.

Table 1: Wireless Generations.

Technology	1G	2G	3G-3.5G	4G	5G
Characteristics	Voice Analog Mobile phones	Voice,Data, Digital,GSM CDMA,TDMA	Video call, Internet,W-CDMA, UMTS,LTE	Mobile IP, Interoperability LAN,WAN,LTE(A)	Tactile Internet,IoT Mobile IP Integrated Networks
Transmission Rate	2 kb/s	<64 kb/s	3.1 Mb/s - 14.4 Mb/s	<100 Mb/s	**<100 Gb/s**
Frequency Band	800 MHz	850-1900 MHz	850-2100 MHz	1.8 GHz-3.5 GHz	**1.8 GHz-300 GHz**
Bandwidth	30 KHz	200 KHz	1.25-5 MHz	1.4-20 MHz	**60 GHz**
Latency	-	<1000 ms	<500 ms	<100 ms	**<10 ms**
Multiplexing	FDMA	TDMA/CDMA	CDMA	OFDMA/SC-FDMA	BDMA/FBMC
Switching	Circuit	Circuit	Packet/Circuit	Packet	Packet
Core Network	PSTN	PSTN	Packet	Internet	Internet
Handoff	Horizontal	Horizontal	Horizontal	Horizontal/Vertical	Horizontal/Vertical
Available	1980	1990	2000	2010	2020

This chapter continues with the methodology followed to write this dissertation and the literature review. Then application scenarios of Tactile Internet are discussed followed by its supporting technologies and a survey on its economic impact. A detailed study of each requirement and why it can’t be realized with current networks will be the subject of the third chapter. In the last chapter, we will present the on-going work on the standards of Tactile Internet from different organizations.

As has been documented in various fora, standardization is far from achieving tangible results. The reason for this is the strict requirements that are associated with the critical nature of its applications together with the relatively high cost of the investment needed in the infrastructure.

The implementation of Tactile Internet over wired and 5G wireless networks will be the focus of extensive future research, for the simple reason that it will shape the distribution of skilled work worldwide, despite justified fears that machines will outperform and substitute humans in many areas.

2 Literature review

Setting the background on what has been explored until now on Tactile Internet is crucial to broaden the knowledge in this field and shape the basis for future involvement in technology projects.

2.1 Methodology

While this is a dissertation around the subject of Tactile Internet and especially its connection with 5G technology, the methodology that was employed is the study and analysis of the recent progress around the aforementioned topic and the presentation of the various technological achievements in support of this vision. Existing research literature mainly focused on the use case scenarios and the requirements of Tactile Internet applications because existing literature in general, around this subject is relatively not very rich. Research also focused on the technologies that were designed for other purposes but could support the implementation of Tactile Internet services. For example, efforts to standardizing 5G are certain to contain specifications for Tactile Internet interactivity. The term Tactile Internet appeared just 2 years ago (August 2014) and the main studies related to this topic and relevant fields are shown below on the Table 2 .

Table 2: Summary of existing related studies.

Domain	Description	Authors
5G White papers	The latest findings related to research activities. Requirements from markets view and technical challenges. Functional architecture and design specifications.	[54],[55],[56],[57] [58],[59],[60],[61]

Tactile Internet	Vision, requirements, use cases, solutions, society impact.	[2],[3],[4],[5]
Network Virtualization	Edge Operating System, Softwarization, Virtualization	[10],[62],[63],[64]
Conference papers on specific use cases	Research and experiments on Reliability, Latency, availability and quality of service.	[6],[7],[64],[65],[66]
Tactile Internet architecture	Recent progress, challenges, technologies and proposed architecture	[1], [3]

2.2 Current Tactile Internet picture

This subsection provides a general view of the literature related to Tactile Internet.

There are some excellent papers on this new technology because it is part of a technological revolution driven by researchers and institutions around the world. It seems that they can be distributed in 3 groups:

1. Research providing general guidelines and description about Tactile Internet capabilities.
2. Specific use cases with simulation in environments with low latency and high reliability.
3. Emerging technologies in other areas that are indirectly related to Tactile applications due to their contribution in meeting some of their requirements.

International Telecommunication Union (ITU) provides in [5] the guidelines of this new technology concentrating mainly on the application fields and the possible approaches in the infrastructure to meet the requirements. Through this framework, researchers can get an idea of the vast potential of Tactile Internet vision. Furthermore, predictions are supported by the expected mobile data traffic increase and the needs that will emerge for the markets.

Furthermore, white papers and technical reports on 5G have been released from major telecommunication companies and they share the same vision: business growth and innovation will be driven by transformation and convergence of ICT network infrastructure. Tactile Internet has a significant role to play in this transformation of societies.

In [1] the author makes a comparison between the three emerging domains: IoT, Tactile Internet and 5G. After a short description of the impact on society, the paper provides a survey of the Tactile Internet concentrating on latency and reliability of fiber-wireless enhanced LTE-Advanced heterogeneous networks. This approach however concentrates mainly with the fiber part in the infrastructure and doesn't deal with the required haptic hardware needed for Tactile Internet applications. Hence belonging to the 3rd group above, it is important that he presents simulation results of average end to end delay and aggregate throughput for different fiber-backed Wi-Fi (Wireless Fidelity) offloading ratios. The conclusion is that it is feasible to implement the Wi-Fi offloading scenario from the cellular networks while keeping low latency in the order of 1 ms. In [2], the authorσ analyzed the contribution of clouds and cloudlets in Fi-Wi (Fiber Wireless) enhanced LTE-A Hetnets in achieving high throughput, reduced latency and increased scalability. According to the authors, the recently introduced concept of LTE-A heterogeneous networks couples the benefits of coverage of 4G mobile networks with the capacity of Fi-Wi broadband access networks. This paper differentiates from the others in that it concentrates on fiber networks experiments, which form backend solution to providing throughput and capacity.

In [3], authors concentrate on the 5G enabled part of Tactile Internet. The paper discusses the recent emerging technologies in the intersection of next generation technologies with Tactile Internet applications. This paper can be considered as an excellent work for the holistic approach of the whole domain since it touches almost every part of the Tactile Internet data loop from the operator up to the actuator.

The authors are quite optimistic in predicting the computational power increase in the next few years although they carefully recognize the challenges of this new technology especially in the mission critical applications. Interesting proposals on technology innovations emerge from the examination of the use case requirements by the authors. Nevertheless, the represented approaches are not further developed with simulation experiments.

More coverage is given to the wireless technology challenges due to the difficulties it represents in the given domain. The proposed network slicing in networks is the basis of the new approach towards meeting the Tactile Internet requirements.

They then propose a partitioning model of the 1 ms delay of the data cycle and propose key changes especially in the physical layer in order to not surpass those limits.

To our knowledge is the only study that proposes a complete architectural design, beginning from the hardware (although not so haptic centric), radio access and core protocols, resource management and edge cloud computing. An interesting fact is the introduction of artificial intelligence at the edge to overcome the physical limit of the speed of light.

A different approach is proposed in [4] and the authors focus on the characteristics of haptic interactions through Tactile Internet and discuss the technology required to enrich the master domain (operator) with high fidelity sensors as well as with powerful computing power in order to translate human senses to electric signals.

They argue that a standardization mechanism for the decoding of human senses is a major step in realizing Tactile applications. I strongly agree with author's view as it will facilitate the way for manufacturers to design and produce haptic devices. However a gradual addition of different sensors is possible due to the increase in the computational power.

The concept of network on demand is similar to the network slicing proposed in [3] involving a logical design of the 5G network architecture based on a common hardware infrastructure. The conclusions are that profound changes to the air interface and physical layer along with caching and intelligence mechanisms will enable the vision of Tactile Internet.

Simulation results in [6] show that it is possible to design the radio access for ultra-reliable and low latency communications. Specifically, the authors investigated communication needs for an automation factory. They used diversity to ensure that requirements are met. They argue that in order to provide a 10^{-9} bit error rate with packets of 100 bits in a 0.1 ms wireless transmission time, the channel must support a bit rate of 1 Mb/s. Thus, the cost of providing high reliability and low latency is the increased bit rate of the air interface. The use of Orthogonal Frequency-Division Multiplexing

(OFDM) is chosen for the air interface as it can be configured according to the needs. While the selection of code rate is closely related to the modulation scheme, it is preferable to use convolutional codes to achieve high speed decoding at the receiver.

The main conclusion is that a tradeoff for data rates is required along with diversity design for high reliability communications. ODFM based 5G modulation is studied in [8] for the same use case scenario. As expected, to guarantee low-latency and high reliability in a factory, it is crucial to analyze the interdependency between bandwidth, antenna configuration and interference power. It does not however consider the desired round trip at 1 ms delay but only one way and what's more important, only for the air interface. It could be feasible to minimize this delay by an order of magnitude by changing symbol duration and cub-carrier spacing in OFDM transmissions.

The diversity approach to achieve high availability in wireless networks in [9] is beneficial not only for reliability but also for power saving. Delivering higher reliability levels using the same amount of power is a remarkable result. It shows that just by redesigning how total power is shared among parallel links, we can guarantee users connectivity.

Another use case scenario is considered in [7] where a vehicle collision avoidance system is analyzed for guaranteeing the Quality of Service (QoS) requirements of Tactile Internet. They model a system with a control base station and many users (vehicles). This work also belongs to the 2nd group. Specifically, the authors consider the latency caused by queuing delay and transmission delays both in downlink and uplink mode. The simulation results support their reasoning in that it is possible to calculate the transmit power, bandwidth and number of antennas in order to guarantee low-latency and low packet losses. The findings however are theoretical and, as expected do not take interference and fading into consideration. Nevertheless it can be extended to include a real life experiment.

A study towards achieving low latency figures in Tactile Internet is carried out in [11] which belongs to the 3rd family where network coding and software defined networking was used. Through simulation experiments the authors compare different network coding mechanisms for end-to-end delay. They found that Random Linear Network Coding (RLNC) (RLNC is a powerful encoding scheme, which in broadcast transmission schemes allows close to optimal throughput using a decentralized algorithm. In addition, efficiency, scalability and security are highly improved) throughout the network is of key-importance to reducing latency and the number of packet retransmissions. The derived performance is significantly better than the End-to-End coding (E2E) or the Hop-by-Hop coding (HbH) schemes. Basically it represents the most general form of network coding scheme which has two features: the sliding window and the recoding. Every node in the network reviews its coding strategy according to network condition for next hop communications. In E2E and HbH, relay nodes use more complex schemes to decode and encode packets so they have a negative impact on latency.

In order to support their theoretical findings, the authors used a prototype software router. It implemented the so called Network Virtualization Function (NFV) and Software Defined Networking (SDN) (discussed in chapter 6) to implement this flexible approach. The software was able to apply the network coding technique on packets.

More specifically, the authors used ClickOS, a high-performance; virtualized software middle box platform for network processing (http://cnp.neclab.eu/clickos) .They also used the Click modular router software. The RLNC encoder, recoder, and decoder elements and fully-fledged compute-and-forward routers were developed by using the Kodo library and its built-in modules, respectively. In addition, a prototype was developed by using the Extensible Service Chain Prototyping Environment (ESCAPE) for the seamless integration of network coding and SDN for a three-hop scenario. The experimental results [11] show that if the channel is error prone, RLNC achieves a lower latency than E2E and HbH coding. Furthermore, it was shown that RLNC and HbH coding increase the total number of conveyed packets in the network linearly with the loss probability, whereas E2E coding increases it exponentially. By contrast, if there are no losses, RLNC and E2E coding exhibit the same latency performance, while HbH results in an increased latency. The experiments on the compute- and-forward software router verified that RLNC outperforms E2E and HbH coding, offering gains on performance up to 6x and 16x [11].

The benefits of software in decreasing latency are shown in [12] where the authors propose an Edge Operating system software (EOS) that will work with edge cloud computing and clouds. The authors used the open source Robot Operating System (ROS) to design their EOS which would provide all the services of an operating system. EOS introduces abstraction at physical edge infrastructure and across different service levels. Services provide functions which are available anywhere, anytime. They are scalable, robust and flexible. Their execution takes place in the virtually- sliced hardware in the form of virtual machines (virtual networks). The management and deployment of virtual machines is critical to avoid overload and increase performance.

More specifically a use case was chosen to represent EOS benefits regarding end-to-end network and application latency. Although this approach is theoretical, the implementation of EOS in mobile cognitive machines use cases requires optimal allocation of logical resources. EOS runs on top of two open source software modules, OpenStack and ONOS which manage and control the virtual infrastructure (virtual machines and service functions). The mobile cognitive machine is a robot which runs its own operating system. The system that controls the robot consists of some ROS nodes for different functional activities. For example, to execute Tactile commands on the robot there must be a proper balance of local, edge and centralized processing resources. Very low latencies are crucial, yet challenging due to the constantly changing conditions, for critical missions.

Furthermore an open source platform called Openstack++ developed by Carnegie Mellon University is built upon the open source OpenStack platform. Its aim is to support cloudlets in the vision of mobile computing. Bringing intelligence closer to the user [13], is the main feature of cloudlets. The authors suggest a cloudlet infrastructure that aligns with the Tactile Internet concept. Apart from that, it can help in automotive environments, wearable cognitive assistance and in remote areas with poor network infrastructure. Another approach in [14] proposes a more dynamic cloudlet concept where all devices in a LAN network can cooperate in the cloudlet.

The new cloudlet infrastructure manages applications on a component level. Components are dynamic parts of applications and can be loaded to different cloudlets according to their critical nature. To support their theory, the authors discuss an augmented reality use case featuring markerless tracking combined with an object recognition algorithm [14]. They claimed that their proposed cloudlet architecture with on demand cloudlets and a component management layer helps high throughput and real- time mobile traffic.

It seems that a study of feasibility is essential due to the high cost of cloudlets deployment. A tradeoff between the investment costs of a dense cloudlets infrastructure and the benefits of progressively low latency will determine the massive adoption. There is high potential in open source software and growing awareness among service providers in order to provide high throughput without delay through the use of cloudlets.

It is also evident that research in the areas of group type 3 is the most important for the standardization of particular technologies that are driven by the needs of delivering content with high throughput backed by big companies. Therefore, Tactile Internet should benefit and coexist with applications of a different nature utilizing the same physical infrastructure.

3 The Tactile Internet vision

A general analysis of the applications family and the economic impact will shape the research towards supporting technologies such as hardware design.

3.1 Applications

As soon as high speed reliable Internet links become commercially available, a plethora of opportunities are ready to be explored. They will either cover existing demand through applications enhancement or trigger people’s interest in unexplored new areas. Developers will also provide us with services and applications that enrich the way all of us live, work, commute, shop, and care for our society, government, health, and environment. Areas of interest include:

1) Smart traffic where vehicles communicate with each other and the environment to increase traffic efficiency and safety.
2) Healthcare with remote delivering of medical services such as surgery, diagnosis and rehabilitations
3) Industry automation in smart control processes through M2M communication to perform complex tasks.
4) Education where virtual classes with instant available multimedia and haptic feedback will enhance teaching experience.
5) Games and augmented reality by integrating Tactile senses in the action and experience a natural perception.
6) Robots remotely controlled in agriculture and harsh environments complement humans in difficult tasks.
7) Energy consumption where the coordination of smart grids helps to increase energy efficiency and lower costs.
8) Sports and entertainment with people enjoying personalized 360 degrees HD content from live events. .

9) Product sales industry where people can touch and feel objects they are interested to buy in exhibitions or online.
10) Assisted training which improves athletes' performance by means of Tactile Internet dynamic interaction from trainer.

These are some of the most important potential applications. It is possible that other applications emerge but at this stage it is not possible to describe using our imagination. It is important that, when designing the Tactile Internet standards, the objectives should be pushed even further. This will be the enabler for possible future applications. As an example, when designing 3G in the 80's, which took 15 years, no one knew that it was going to support applications on mobile phones in the early 2000. However, at periods of strong global competition, we should try to minimize the gap between what standards promise and what they really achieve. By doing so, it's more likely to get accepted from users without the "people resist changing" etiquette.

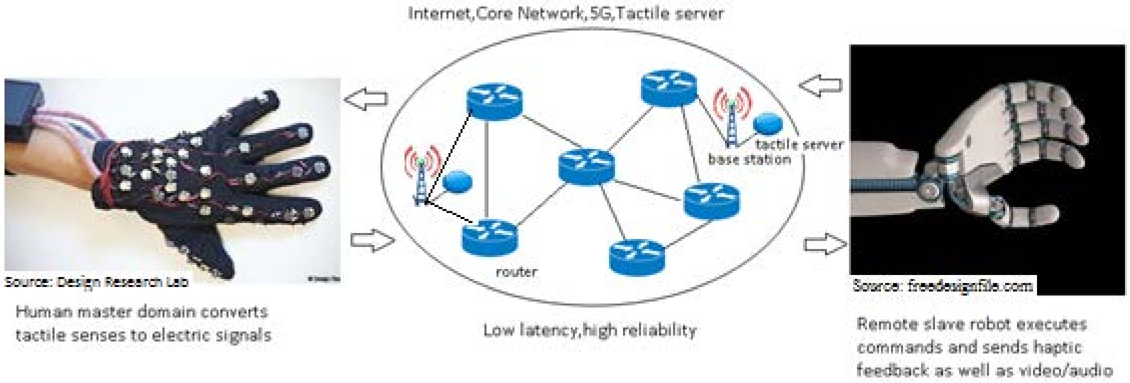
3.2 Supporting technologies

Tactile Internet requirements imply a better understanding of human Tactile senses and their integration with the digital world. The Tactile sense is a primary sense we use on a daily basis to process information from the environment. It is vital for communication, interaction and performance. Receptors for the Tactile system are located in the skin. It has therefore the widest area of receptors of all the senses. We use touch to feel and discriminate our surroundings.

3.2.1 Haptic Interaction

IEEE Technical Activities Board (TAB) launched in 2015 the IEEE Digital Senses Initiative (DSI) as an IEEE-wide initiative. With a deeper understanding of how human senses work, we will be able to bring disruptive innovations into the areas of virtual reality, augmented reality, and human augmentation. IEEE, through its Digital Senses Initiative, is taking the lead in advancing technologies that capture and reproduce, or synthesize the stimuli of various senses (sight, hearing, touch, smell, taste, etc.); combine the reproduced or synthesized stimuli with the naturally received stimuli in various ways; and help humans or enable machines to perceive, understand, and respond to the stimuli. Plans are underway to capture all the different perspectives via in-depth crossdisciplinary discussions, and to achieve a set of results which will facilitate disruptive innovations and foster cross-industry collaborations globally in three focus areas (virtual reality, augmented reality, human augmentation) and many other relevant areas (smart robots, wearables, consumer healthcare, etc.).

The most important innovative service we encounter in Tactile Internet applications is haptic communication (Picture 2). Sensors convert Tactile parameters like contact, location, pressure, shear, slip, vibration, temperature and kinesthetic, like position, orientation, force, into electrical signals that are transmitted where the commands are executed. The combined total latency must be under 1 ms for total immersion in the remote environment.



Picture 2: Haptic interaction through Tactile Internet

Haptic communication differs from video/audio because Tactile commands are paired with their feedback from the actuator side. It is a bidirectional communication that provides experience close to the natural one. When for example force is applied on an object, it reacts with the same force. This reaction is captured and is transmitted back to the glove through pins and needles which exert pressure as required by the algorithm. Similar technologies include stretchable sensors and fabrication technology. These extremely thin and flexible sensors can measure human skin parameters. Significant research effort has been devoted to fulfill the technology requirements of future technology.

Early efforts have led to the development of a 2D Tactile Internet application (TAC2020) device by Huawei than can precisely and instantaneously reproduce the movement of a human finger on a touch screen, therefore introducing a remote drawing machine. TACTIP from the Bristol Robotics Laboratory is a Tactile fingertip for robot hands while GEOMAGIC (Picture 3) and SENSABLE have released commercially available products which allow a 3D navigation and provide force feedback integrating the sense of touch.

Picture 3. Geomagic (Source: geomatic.com)

Widespread adoption of haptic devices requires low cost systems that integrate Tactile with kinesthetic sensors. In addition, advanced network capability must be added to comply with next generation networks.

Haptic signals need to be digitized and just like voice and video, future work will focus towards standardization of haptic data flow. This will help vendors to produce compatible reliable products. The slave robot sends haptic data with audio visual feedback.

There should be a multiplexing scheme that encodes data from different sensor streams. However, apart from simple force/torque sensor systems with 3 degree of freedom (DOF) for multiplexing with audio and video, other complex combinations add significant computational load on the system. These schemes must provide QoS for different tactile data since the human perception of environment relies on the timely combination of senses. For example when hitting an object remotely, it combines touch vison and audio in perfect coordination. These senses have different characteristics in terms of frequency, transmission rate and latency.

Furthermore, the real time approach cannot be implemented using state of the art protocols such as TCP (Transport Control Protocol) or UDP (User Datagram Protocol). The first includes overhead and the second unreliability. 5G will make possible a reliable and secure haptic communication by implementing NFV and SDN .This will integrate network functionality in any cloud computer system using the software module approach. While SDN provides the architecture where control and data are decoupled it enables direct programming of network control through software controllers (to be discussed in next chapter). Further research must focus towards improving QoS metrics of haptic interaction through wireless channels.

3.2.2 Progress in electronics

Tactile Internet has put strict requirement on ultra- low latency. Hence, to achieve the end to end 1 ms latency physical limits need to be taken into consideration. The maximum distance light travels within 1 ms is 300 km. It is impossible to break physics laws so one way communication distance for Tactile Internet operations has a theoretical upper bound of 150 km. In practice delay happens due to:

- The actual distance travelled is longer due to light bounces along the fiber making it resembling a zig zag instead of a straight line.
- The actual signal speed through fiber is some 30% slower than through vacuum.
- The more network equipment the signal has to pass through (switches, routers, repeaters), the longer it will take to reach the other end because of processing and delays.

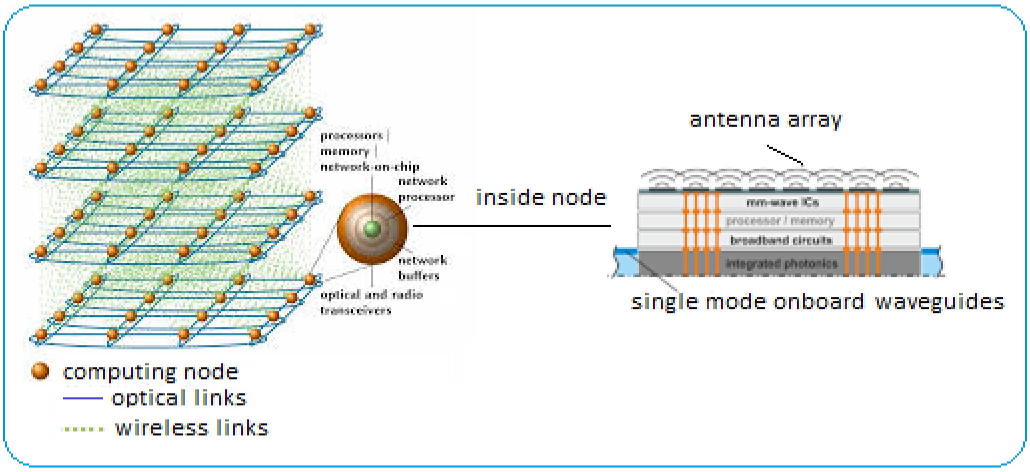
Thus, a more realistic scenario puts the one way Tactile interaction to a maximum distance of a few tens of km. Therefore the Tactile Internet servers need to be very close to the base stations if not integrated in the same equipment. This is the concept of Mobile Edge Cloud (MEC).It consists of highly efficient and adaptive equipment that practically minimizes computational and processing delays. However, how can this be possible with present electronic advances?

In order to have a clearer picture, it is important to look at the present trends. Since the invention of transistors, computational power and memory has doubled approximately every 2 years following Moore's law. More power and memory for mobile devices put stress on the networks regarding the efficient transport of massive data. The 2D integration however is slowing down and estimates are that within 5 years it will come to an end. It will not be possible anymore to decrease transistors size and increase integration.

Apart from that, there is the energy issue. In 2015, the global share of the Information and Communication Technologies (ICT) in the total electricity consumption exceeded the 7 percent threshold. Within ten years the demand has doubled with rising tendency. A considerable share of the consumption is taken up by computer centers. European

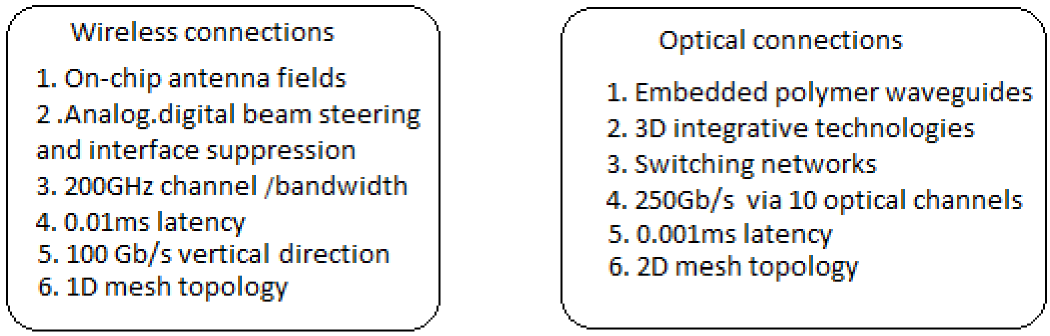
Union Key Action 12 of the Digital Agenda sets criteria on implementing Green ICT solutions. So, in the future, highly efficient computer technology is required which is low energy consumption and high-performing at the same time.

These two key challenges are expected to be addressed by the Highly Adaptive Energy-Efficient Computing (HAEC) Box envisioned by scientists at the DFG's (German Research Foundation) Collaborative Research Centre 912 – at the Excellence Cluster Centre for Advancing Electronics in Dresden. Extensive research takes place in order to reduce the energy consumption of large computer platforms, such as computer centers, while executing applications as fast as possible. Present solutions do not meet the requirements of future demand.



Picture 4: HAEC Box (Source: tu-dresden.de)

The long-term research goal is the HAEC-Box (Picture 4), which represents the vision of a high-performance, energy-optimized device with 100 million computer cores contained in a volume of just one liter. It integrates wireless and optical functionality in a 3D stack chip technology. In this space-efficient arrangement, computing nodes communicate by means of horizontal optical interconnections and vertical wireless interconnections. High efficiency is achieved through point-to-point one hop vertical wireless links and horizontal optimal topology usage. The main characteristics of wireless and optical connections are shown in Picture 5. It is clear that both technology throughputs are comparable.



Picture 5: Wireless vs. Optical connections

Real time synchronization of user demands with network functionalities and computational power may be supported by real time operating system. Nodes and links are switched on only on demand to save energy. This powerful server can be deployed close to base stations to empower critical Tactile Internet interactions. Furthermore, there is no significant change in present architecture.

Tactile Internet services are the main potential beneficiaries from this concept. Three orders of magnitude improvement of I/O throughput and latency are key to bringing to success future Tactile applications.

3.3 Economic impact

The characteristics of Tactile Internet make it an important driver for economic development. It is a breakthrough on how today's networks will get transformed from a static information delivering infrastructure to a dynamic one. Its ultra-low latency, high availability, reliability and security will be characterizing applications in the next decade. It is something totally new which will shape and impact our society. Therefore, Tactile Internet will affect every part of our activities, especially in developed countries with service oriented economies like Europe and the US. Its predicted fourth industrial revolution will impact many sectors. New market opportunities will be created in highly benefiting industries like healthcare, industry automation, traffic and energy. The improvement of safety and security standards on the roads, dynamic smart control of energy flow, personalized healthcare are some of the direct effects of this technology.

These new features will bring business opportunities for application developers, vendors, consumers, businesses, telecommunication companies, even insurance companies and law makers. Tactile Internet will create ground for technical and business innovation. Moreover, as network services are provided through software development, start ups growth will be expected in this area.

• A preliminary market analysis revealed that the potential market could extend to 20 trillion US dollar worldwide. This is around 20% of today's worldwide Gross Domestic Product (GDP) [3]. According to the most recent European green paper on m-health, it is expected to reduce costs on healthcare by 15% by increasing the effectiveness and efficiency of care delivery. Healthcare costs estimated at 10% of Europe's GDP and a growing ageing population is the main beneficiary of Tactile e-health. Reliability and low latency in smart grids will significantly reduce the cost of energy of many geographically dispersed small electricity producing companies. New business to business (B2B) partnerships will emerge especially in the telecommunication area. Because of the high traffic and computation at the wireless edge cloud, companies providing content and data control will have to deploy powerful servers with artificial intelligence close to telecommunication companies infrastructure. The <1 ms latency will increase the market share of such companies because of the need of decentralization of networks i.e. pushing intelligence towards the users. On the other hand, the incredible amount of data analytics is going to provide operational efficiencies across multiple industries. It is going to stress how network providers function from billing, provisioning and customer service perspective. Manufacturers of user end devices will expect their share to rise. Moreover, 5G enabled content delivery experience will not be possible with existing equipment.

An interesting study for the European Commission on the socio-economical impact of 5G in EU member states presented in March 2016:

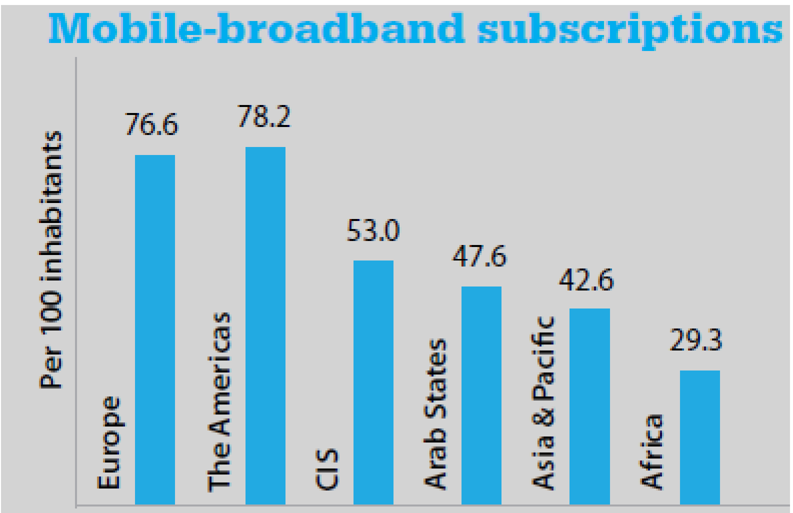
• "*This study provides an insight to the perfect scenario if Europe can maximize the benefits of 5G. It fills a major void in 5G research by forecasting the quantitative socio-economic benefits. The study focused on 4 verticals (automotive, healthcare, transport and utilities) and 4 environments (smart cities, non-urban areas, smart homes and workplaces) to investigate the impact of 5G in EU. Forecasts suggest that 5G deployment costs will be approximately €56 billion. The study investigated spectrum challenges and spectrum needs of 5G. Analysis showed there will be a requirement to share spectrum in all the spectrum ranges.5G is expected to generate benefits of €95.9 bn per annum in the four verticals in 2025. Benefits of €50.6 bn are expected in the four envi-*

ronments. 63 per cent of these benefits will arise for business and 37 per cent will be provided for consumers and society."

Tactile Internet will rely on 5G networks to offer its reliable and secure services. Its huge capabilities will change industry by the next wave of productivity. Every sector changes at its own pace. Bigger companies acquire the successful smaller ones. Business models and even players will change depending on how fast they adapt to the new technology.

Developed countries have the means to attract investors to invest in next generation networks. The Return on Investment (RoI) will depend on how vertical industries such as car manufacturing will include advanced mobile technologies in their equipment. There must be assurance that mobile services will be available throughout the lifecycle of their products without the unjustified increase in prices. The concept of trust between telecommunication companies and industries requires backward capability to be totally functional. The pre- 5G equipment must be seamlessly integrated with the new technology.

The adaptation of Tactile Internet from consumers requires intervention in infrastructure to improve access figures of population to mobile broadband technology. Although Europe (Picture 6) is a leader in mobile-broadband subscriptions with penetration about 77%, still about one fifth of Europeans do not use the Internet.



Picture 6: Mobile penetration (Source: ITU)

A clearer picture is on the network side where 4G will account for 60% of Europe's mobile connections by 2020. This will be driven by 4G network coverage of over 80%

of the European population in the end of this year and a prediction of 95% by 2020, when an early implementation of 5G is expected to take place.

4 Application Scenarios

Potential Tactile Internet applications are expected to be developed for many activity areas in which they are going to fill the gaps of the cyber- to- physical integration and make technology feel more natural.

4.1 Transport systems

A key factor in the economic development is transportation. The problems associated with it are known, from traffic congestion to accidents and air pollution. According to World Health Organizations (WHO), road accidents annually cause approximately 1.2 million deaths and 50 million injured worldwide. Traffic congestion costs Europe about 1% of GDP every year. Tactile Internet will greatly eliminate those figures by introducing new communication standards. Its implementation will also improve fuel efficiency and air quality. Imagine vehicles running at steady speeds, equal distances from one another.

Picture 7: Cars communication (Source: Techmaich.com)

Traffic optimization will make traffic lights belong to the past. Powerful processing capability installed on vehicles will make possible real time calculations of the surroundings and communicate the position and any related information to the nearby cars.5G wireless links enable high-reliability, ultra-low latency and massive links. So a car will have a full picture of traffic even if it is beyond the capabilities of its own sensors (cameras, radars, IR equipment).This makes possible the complete avoidance of collisions through the instantaneous information exchange. The distance covered by a car during a stop command will not be a factor of communication delay since it will be in the order of 1 ms. Braking distance will not be influenced by the reaction time of the driver. Traffic in the cities can be efficient due to the small distances between cars. However vehicles travelling at 100 km/h in highways (Picture 7) will need to keep safe distance ranging from 40 m to 94 m. It depends on the car and the road conditions which are provided as a feedback to the car brain. Based on this picture, several specific situations can benefit (Notice case I and II do not fully comply with the Tactile Internet since touch may not be involved):

I. Emergency vehicles

When every second counts, it is a matter of life or death for the emergency vehicles to reach the hospital, the burning building or the crime scene. Tactile Internet can provide super-fast message propagation to the preceding vehicles. Cars are aware of the ambulance only when they are within the reach of sight or are able to hear the siren still not knowing the exact path it's going to take. However, with this technology they will react and make way far in advance.

II. Hidden objects

A car detects a danger on the road and transmits the information to the surroundings so that nearby cars are aware of the dangerous locations such as works in the road infrastructure, out of sight curves, slippery part. High-reliability will extend the use to the pedestrians and the bicycles. By using similar equipment (e.g. smart phones) they advertise their presence to the surroundings and minimize accidents.

III. Coordinated communication

Beside vehicle- to- vehicle communication, which is a kind of self-organized network, there is the need for centralized communication where the human factor takes control using Tactile technology, for example remote driving in case of the driver not feeling well or difficult driving conditions. Operators in public places such as stadiums, malls or construction sites may warn incoming cars for possible congestion and propose rerouting alternatives either to parking places or different roads.

Future Tactile systems will need to support remote control of specific tasks like metal mining or wood processing. The benefit of this type of use case is to remove the need for people to work in hazardous environments or maybe to increase efficiency by being able to manage different machines simultaneously, reduce cost, and save time when drivers are not available.

The ability to transport high quality video, audio and other information from the remote machine's environment to the controller is also important here.

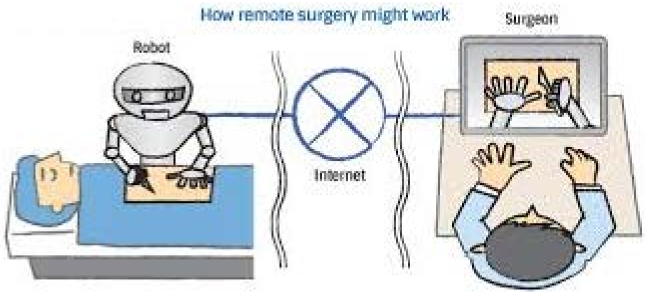
Real time remote operation requires the latency of the communication link between the machine and the controller to be extremely low. This strict requirement not only imposes requirements on radio access, but also on the transport and Core Networks (CN). In such scenarios, long transport links should be avoided, and processing may need to be moved closer to the machinery or to the remote controller. Furthermore, as the remote machines are likely to be on the move, the supporting network infrastructure will need to be able to adapt to mobility.

No existing technology meets the strict requirements of these safety use cases. Dedicated Short Range Communication (DSRC)(mainly 802.11p) and the WLAN based V2X communication do not fall below the 10 ms end- to- end with the cost of a DSRC system not affordable for massive use. Apart from that, special care must be taken to continuously test sensors accuracy. A complete hardware sensor failure is easily identified and can be either replaced or some action can be taken via fail-resilient mechanisms to correct errors. However problems arise when there is a gradual degradation of hardware in which sensors output differs significantly from the actual measurement. An erroneous important sensor's value might in this way get propagated to a large number of vehicles and cause unexpected results. Strict requirements must be defined for data ranges that are produced from sensors, especially those that are used for safety applications. Continuous performance testing must be carried out in order to guarantee reliability.

4.2 Healthcare

The most promising at the same time challenging field for Tactile Internet application scenarios is healthcare. Its projected market share of IoT applications will be 41% by 2025. Along with industrial automation, these are the 2 main application scenarios that will benefit most from Tactile Internet technology. Medical technology innovations will be delivered worldwide and will eliminate the cost of travel. A patient will have the choice of being treated by a doctor without being in the same physical location. The strictest requirements of medical applications are not only minimal latency between action and response but also real time haptic feedback, optical and visual information. Redesigning the network architecture is vital because of the critical nature of this field.100% reliability must be guaranteed in order to make the market exploitable. Some use case scenarios include:

- Remote surgery (Picture 9) is by far the most promising application in the medical industry. It will improve patient's life quality by minimizing the period of hospital treatment and medical costs. It makes possible the involvement of highly skilled doctors in operations that take place in another continent. In addition it also facilitates groups of doctors from different locations to take part in teamwork.



Picture 9: Remote surgery (Source: financegreenwatch.org)

A movement of a robotic arm by a doctor in a remote location requires both-way data transfer. Some data packets control the medical robot movement and some get the result on a screen. Interesting, though, it is reliability which matters most, provided that latencies fewer than 200 ms are guaranteed (Below this threshold, surgeons cannot detect time lags). Reliability requires that operations must be shielded against attacks or network flooding conditions that put stress on QoS metrics. By using powerful cloud computing in the future, big data gathered from hospital surgeries must be analyzed for best practices and results. Training of future surgeons will be performed with these data using virtual remote simulation experiments. So there will be a paradigm shift towards complete digitalization of hospitalization industry. There already exist some robotic surgery systems that operate efficiently over meters away from patient such as Da Vinci or ZEUS. However, state of the art network architecture cannot be used over long distances because of high-latency and reliability problems of data transmission. Moreover, the usage of dedicated fiber optic lines, though secure, is cost prohibitive .Tactile Internet empowered by next generation networks is expected to address these issues. Apart from the benefits however there will be social issues that we can't even imagine. What is the feeling of the patient being operated by a surgeon kilometers away? Furthermore, because patient psychological conditions play a significant role in the final outcome, who is responsible for any potentially negative results of the surgery?

- The development of diagnostic systems through Tactile Internet is essential in hospitals with limited number of doctors. Tele-diagnosis reduces duration to waiting lists for taking specialized health care. Similarly to remote surgery, it allows timely diagnosis and treatment by providing primarily healthcare services in remote areas avoiding thus unnecessary travel cost and time benefiting the patient. In addition, tele-diagnosis overcomes geographical barriers providing specialized healthcare services to places and situations where they are considered a luxury (e.g. Africa).
- 'Mobile-baby' is a mHealth service being implemented in Nigeria and Tanzania (known as 'Safer Deliveries' in Tanzania). This service is the result of a partnership between Etisalat, Qualcomm, D-Tree International and Great Connection. The service is aimed at reducing mother and child mortality by helping pregnant women in rural areas reach hospital. 'Mobile-baby' allows medical practitioners to send ultrasound images, video clips and 3D scans directly from ultrasound machines to mobile phones via SMS, MMS and email, providing real-time remote medical diagnostics.

It protects doctors from working in harsh environments. Getting haptic feedback from the remote patient could be the most valuable innovative medical achievement. Tactile gloves make use of <1 ms latency and reliability to accurately examine patient condition. Tele-diagnosis is already applied but it involves only voice and video which are delay tolerant. Touch on the other hand will provide the doctor with the complete picture.

• Tele-rehabilitation and recuperation will provide services to patients with disabling conditions which need constant care from medical staff. It introduces the use of proper equipment (ex. exoskeletons) which is applied to the patient body and guided remotely by physicians. Again, the same next generation technology is applied to steer and control patient's movements. Advantages are personalized treatment, quick response times and faster recovery period. Patients in need of periodical medicine injections will also benefit using bidirectional Tactile equipment controlled by a nurse.

4.3 Education

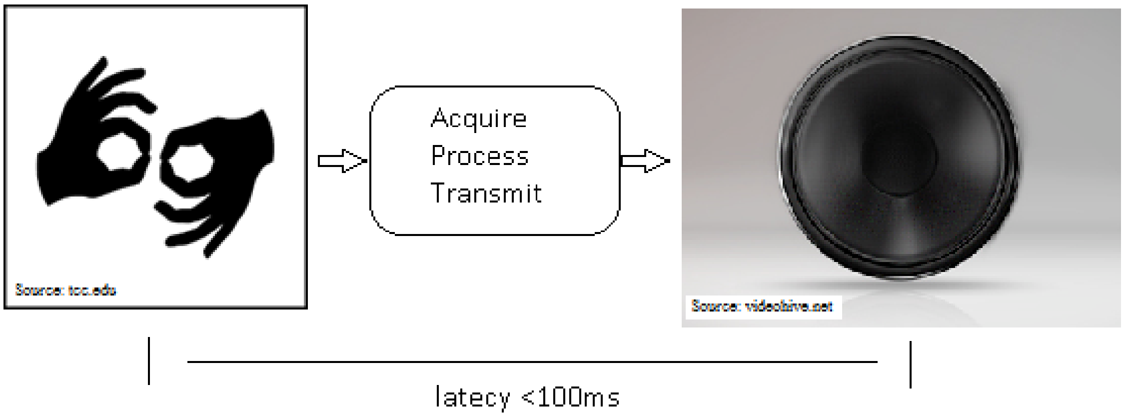
Tactile Internet is expected to create new applications in the field of education. It will add a new dimension to distant learning by ensuring that every talent gets exploited by a tutor or a teacher. Today's digital generation spend more time in online applications. The natural feel like of virtual environments will enhance the educative experience. The transmission of skills without delay means designing the education industry on a new basis. Large throughput, Tactile feedback and low latency create an interactive environment which has the following benefits:

1. Real time active experience
2. Available anytime anywhere
3. Can include all kinds of senses
4. Makes complex things easier to understand
5. Reprogrammable
6. Safe to use
7. Cost efficient

Consider e.g., learning of a new instrument where a significant involvement of the tutor is necessary. Tactile Internet enables the real time transmission of tutor's touch sensing eliminating the need for physical presence. Virtual classes where students enjoy interactive high quality information about history, archaeology and arts stimulate their inquiry skills and allow them to better understand the scientific content.

For example, children in Spain with certain diseases, who typically spend many hours in the hospital, can now "visit" the zoo virtually through a live 3D video feed, as part of an ongoing study by the Malaysia-based Institute and the University of Valencia to see if virtual zoos have a positive effect on the children.

In addition, personalized and customized education brings out the best from each student. Students with speech disabilities can benefit most by enabling a communication bridge with the rest of the class. The use of Tactile gloves will provide the source of a fast streaming encoded data that can be instantaneously converted into speech.



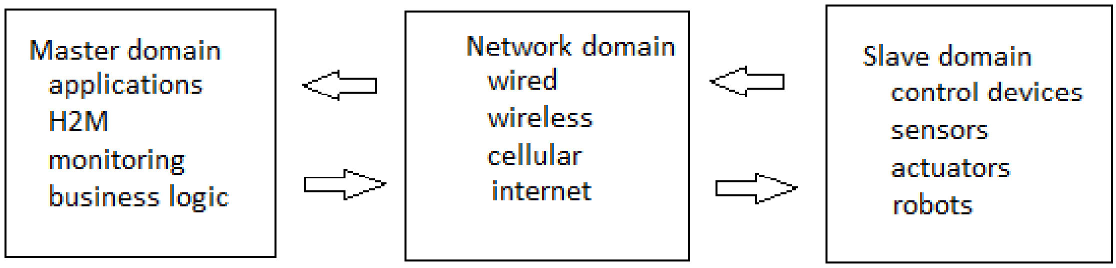
Picture 8: Sign language (SL) is translated into sound either by Tactile gloves or video processing.

Imagine a Tactile application that takes SL as input and outputs translation into spoken language (Picture 8). The other way around is also true when language is translated into sign. Other than a low latency requirement, high computational power and network throughput means that video and image processing needs to be done close to the Tactile edge. Craftworks such as drawing and pottery could also benefit. Embedded sensors transform friction and force into electric signals which are transmitted to the Tactile edge ,translated into friction and force and passed on to an actuator which shapes the model.

4.4 Industry automation

Increased demand for productivity and efficiency in industry has given rise to research in Machine- to- Machine (M2M) communication applications in the context of 5G next generation networks. Tactile Internet will reshape automation especially in manufacturing with the implementation of low latency, reliability and security requirements. The goal is to introduce technologies that improve resource handling, coordinate processes in the demand-supply chain, and increase competitiveness to adapt to global challenges. The current infrastructure consists of wired industrial networks which connect sensors, actuators and mobile devices. However inter and intra-factory cooperation requires reliable, massive throughput and ultra-low latency wireless communication channels to help scalability and flexibility.

Wireless infrastructure covers remote areas otherwise unreachable by wires. The increasing need for mobile productive machinery requires reliable communication throughout the topology. The three main components (Picture 10) of the industry infrastructure are continuously exchanging data and control packets. As computational power of servers and mobile devices increases, along with the reliability of sensors and actuators, the bottleneck for industry has shifted to communication model.



Picture 10: Factory model

The network domain handles data from the slave domain to master domain applications.H2M, M2M and Machine Type Communication (M2C) is supported through network protocols .In case of failure, a message is transmitted to the supporting unit either in-house or at vendor's facilities. In this way, real time tracking of industry processes is achieved and fast service intervention times, as well as self-healing capabilities of the components of the slave domain.

It is clear that in such a heterogeneous environment, a single network protocol or wireless communication solution is not enough. The shift to wireless coverage paradigm requires dense support of connectivity from the end devices to a single access point. Safety applications and massive control in critical industry environments requires reliability of over 99. 99%. There are other industrial applications that rely on HD video to control processes. That requires high data rate systems availability. Various communication protocols need to be implemented because of the different mobile scenarios concerning devices that interchange often access points with macro cells.

Another important requirement is battery life of a hard to reach physical device.5G proposed standards that will be applicable in industry, require a >10 years lifetime.

State of the art industrial wireless networks WirelessHart and ISA100 are used as low rate wireless personal area networks. As these technologies operate on very low power, the battery will last for a longer duration. Both wireless technologies are based on the IEEE 802.15.4-2006 standard and operate in the unlicensed 2.4 GHz frequency band. However their disadvantages are that device compatibility between different vendors is not met. They do not have high throughput which might be necessary for firmware updates. Although with ISA100 the designers offer more flexibility in network design as well as with the implementation of IPv6, there are security issues that are left to the vendors' choice of hardware and software, thus, making this technology vulnerable to attacks. As a conclusion they are not candidates for next generation industrial wireless systems.

Some of the technologies that are being proposed for 5G will be implemented in the 5G standard and will address these industry issues

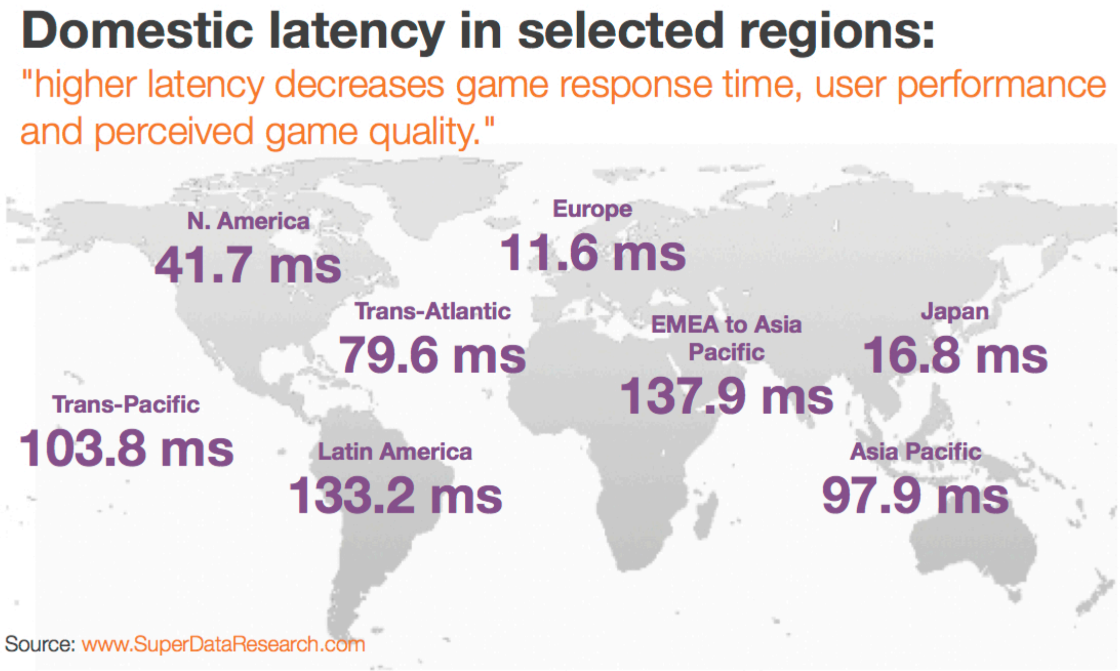
4.5 Sports, Entertainment

In many sports such as skiing, snowboarding, swimming, rafting athletes are not able to communicate during the training with their coaches and get feedback on their performance. Because of the nature of these sports, coaches have only visual contact with athletes. Tactile wearable training suit can provide feedback and help a coach to give commands and correct athletes' posture. It has been shown lately in sports that extensive usage of gathering data from athletes' increases performance and entertainment levels. For example, during a football match athletes wear a bracelet transmitting their speed, position and endurance. This data is analyzed to get the individual top level performance and to make necessary afterwards training to improve several characteristics of an athlete. Taking it a step further, during swimming a coach cannot have audio feedback from the swimmer. Therefore, he cannot give advices on how to adjust timing and tempo. Wearing Tactile suit (waterproof obviously) Tactile feedback is possible. The coach can transmit body adjustment instructions to the swimmer. By pressing a button on a computer he might trigger a pressure on the wearable in the neck that might be translated into a "keep head down" command. Similarly instructions will be transmitted to all parts of the body to correct mistakes and adjust proper body posture. This is impossible to be realized without <1 ms latency. This real-time interaction will be possible only with next generation networks.

The challenge here is to agree on a global Tactile language that fits to all applicable sports for example how are commands like strech, bend, faster, going to be accurately translated.

- 5G networks must meet the requirements of throughput during a football match where hundreds of cameras give live streaming of different coverage areas in the stadium. As a matter of comparison, to cover SuperBowl50 a network infrastructure of 1300 AP (Access point) was developed with traffic expected to exceed 10 TB.With an average of 25000 simultaneously connected devices, traffic for each device is 400MB with the ratio DL/UL less than 1,5 (!).This is orders of magnitude smaller to what 5G envisions, where a spectator might follow the match in the mobile phone from different angles .Cameras attached to players allow for customized streams as to how a player moves around and what he sees. This is HD video, 10 Gb/s raw data, massive throughput which cannot be compressed because it introduces delay. Todays' compression techniques achieve latencies of 50 ms but it requires some tradeoff of decreased video quality. So, Tactile Internet will eliminate the need for buffers, encoders and decoders and all latency contributors.

- Gaming is where latency matters most in terms of customers' satisfaction. This industry is going to reach $1 billion by 2018.The majority of these is distributed and played over the Internet, but the transition from offline to online gaming had to deal with many challenges. The paradigm from classic game to online versions created pressure on developers and publishers to be able to predict consumer demand so that they provide excellent gaming experience. The physical limitation of the underlying hardware like switches, routers and network congestion make latency vary from time to time. A player interacts with many players in massive multiplayer online games. Some of this information can be lost due to delay. Information has to be delivered within a time limit so that the responsiveness of players is maintained. Acceptable delay varies in different games from 50 ms to 1s.In general, delays of over 500 ms during a video game, increase the possibility of players quitting the game to 100%. Latency has a negative impact on game experience as the real time perception diminishes. A related problem is that you can't have players with different latencies because those with low latency will have an advantage on game outcome. Geographical position also plays a significant role in latency outcome. If there are players from Europe and N. America (Picture 11) and servers are situated in Europe then European players are expected to experience better game perception.

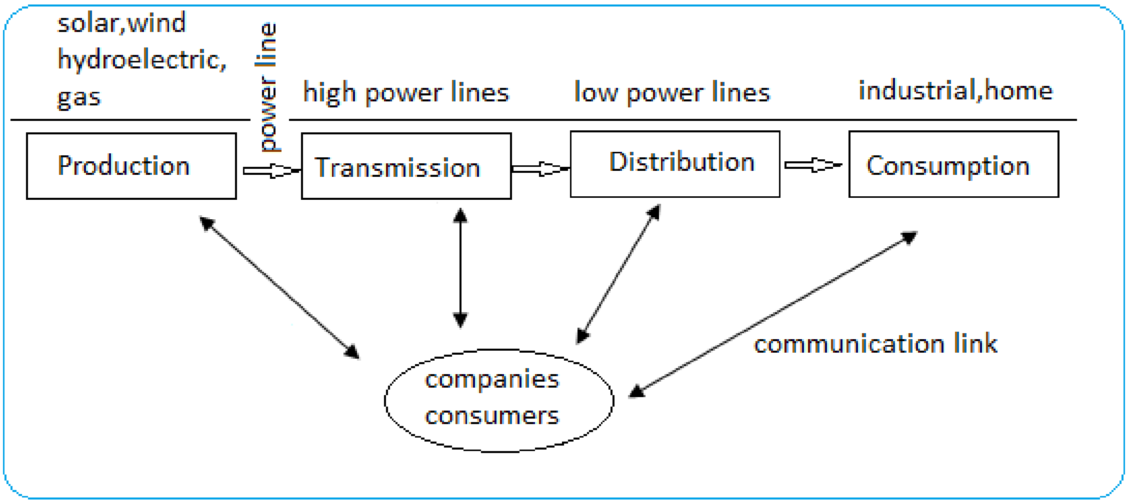


Picture 11: World latencies (Source: superdataresearch.com)

Game companies have tried to solve these issues by adding more servers to distribute the load through peer to peer or multiple vendors and locations. The first solution increases costs while the other requires changing or diversifying architecture using Hybrid Cloud. The vision is to have a near zero latency experience for video games that approaches real world interactions delay and that is expected to become reality by the Tactile Internet and its distributed cloud infrastructure artificial intelligence capabilities.

4.6 Energy savings

Highly increasing electricity demand in recent years has given rise to distributed power system plants. The industry is shifting from centralized, where there is a single point of power production, to decentralized, where there are smaller energy production systems geographically distributed to minimize distance from industrial or home consumers. The effort to control power production, transport and distribution gave rise to power plants with advanced information and communication technologies or smart grids. In order to meet the requirements of the industry, 5G and Tactile Internet is going to offer reliable, high speed and secure communications through H2M interaction. Because electricity cannot be stored, there is the need for better coordination through the whole energy process flow (Picture 12).



Picture 12: Energy and communication links

The challenges that a distributed power system faces are:

a) Operating problems (failures, voltage fluctuation, phase coordination)

b) Market efficiency (predict demand, supply, cost)

c) Consumer satisfaction (pricing, monitoring, plans' flexibility)

These problems can be handled by using new generation technologies. Because of the distributed topology of smart meters, massive wireless connections with low latency are required to transmit data bi-directionally to companies' management applications. The advantage here is that topology changes very slowly and mobility is not an issue. Nevertheless, latency is also critical in coordinating the production in terms of demand. Production units rely on renewable energy resources which do not produce electricity at a constant rate. Voltage readings vary, so it's critical to keep adequate consumers supply level, but on the other hand to save on generated power by introducing consumer awareness programs. At all phases reliable sensors are needed which communicate possible failures that require immediate fix through either selfheal or remote intervention through Tactile Internet. High throughput is required in terms of live monitoring of critical infrastructure elements.

Finally, because there are millions of devices interconnected in a heterogeneous network, this gives birth to security issues:

1. Topology is by itself an issue because it is highly distributed making physical access to any infrastructure elements easy.

2. A large number of networked devices means probable target for hackers with unpredictable results, especially in the control layer.
3. Consumer privacy issues arise from massive data being gathered into companies servers as to who has access to this information.
4. Different players (producers, distributors, wholesalers, and consumers) from different backgrounds need to be coordinated efficiently.
5. It inherits all security issues of the Internet as it uses its protocols for communication.

By implementing security in the physical layer, smart grids will benefit from Tactile Internet technology. It will consolidate their role as the primary driver for economic growth.

5 Challenges

In this chapter the challenges of Tactile Internet are analyzed from the network perspective. The way to address these challenges is to better understand and trigger changes in current networking technologies.

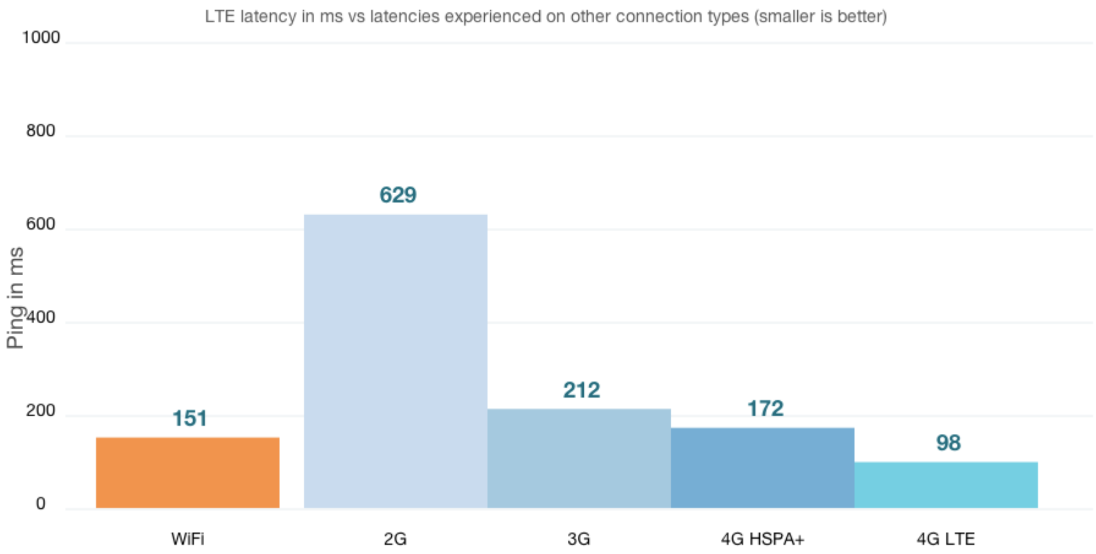
5.1 Latency

The most important requirement of Tactile Internet that will shape the design of future networks is its end- to- end delay that must be under 1 ms in order to experience true real time interaction with the environment. If not, an erroneous perception is caused from poor coordination during digital feedback of human senses.

Round-trip latency is an important design parameter for modern mobile networks because it has a very large effect on the end user's perceived Quality of Experience (QoE). Communication latency has a similar influence as packet loss on the quality of interaction and may lead to undesirable effects on user satisfaction and usability. It is key to haptic and to mission critical applications that were discussed in chapter 2.

Latency is the time interval between action and reaction in a communication channel. In other words, when a data packet is transmitted and returned back to its source, the total time for the round trip is known as latency. Its lower limit is imposed by the communication medium and it affects the throughput as it is directly related to the amount of data packets that is travelling at given moment.

Latency is important, not only for Tactile Internet applications but also for other services. For example, a study from Amazon some years ago found that every 100 ms increase in latency costed the company a 1% reduction in of sales. And that means over $800 million lost in sales for 2016. In capital markets, a large global investment bank has stated that every millisecond of latency results in $100 m per year in lost opportunity.



Picture 13: Wireless technologies latency (Source: Opensignal)

Latency in wireless standards clearly shows (Picture 13) figure improvements in practice with the LTE technology. However this is too far from the required 1 ms end- to-end delay.

The main cause of delay in wireless medium is fading, but in general in a network transmission, the following four factors contribute to latency:

1. Delay in Storage: In both Tactile edges a packet may be subject to hard disc access delays at intermediate devices such as switches. When writing or reading data from different blocks of memory on hard disks or other storage devices, a delay occurs mainly because processors often consume a lot of time finding the exact location for data manipulation. Significant steps need to be taken in order to minimize the bottleneck effect of storage delay in Tactile engines.

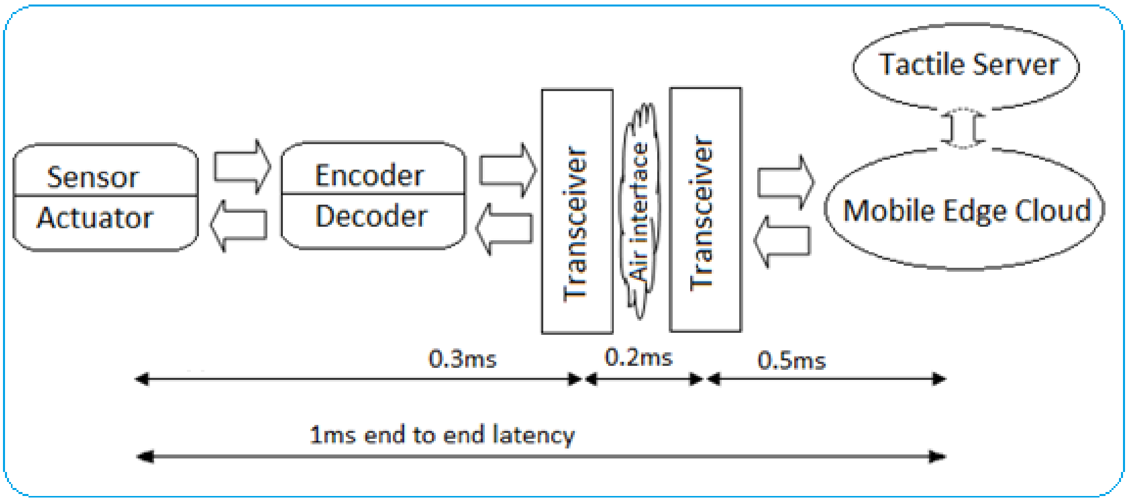
2. Device Processing: Latency is not limited to storage devices but can also be caused by different network devices. For example, when a router receives a data packet, it keeps that packet for some time to examine its information and header or adds some extra information. So generally a network route with the fewest number of hops is desirable for Tactile Internet (although this is not always the case, since some links may be faster than others)

3. Transmission: There are many kinds of transmission media and all have different characteristics. Each medium, from fiber optics to coaxial cables, takes some time to transmit one packet from a source to a destination. Packet size plays a signif-

icant role in latency in a round trip since for a larger packet will take more time to reach their destination than small packets. Therefore, to enable Tactile interactions through Internet, packets data must remain small.

4. Propagation: Delays occur even when packets travel from one node to another at the speed of light. Refraction and bouncing phenomena contribute to further delays. This simply puts a threshold on how low a latency can be for a given transmission distance.

The sum of the above delays is the total latency. So in order to provide a 1 ms total end-to- end delay we have to examine the latency share of these factors in a Tactile Internet application. This includes the time for the transmission of data from a sensor through the communication channel to the actuator. As shown in Picture 14 , a hypothetical latency budget share is divided between parts of the Tactile Internet chain.



Picture 14: Hypothetical latency share in Tactile Internet

The worst case scenario (although this is often not the case) involves an air interface during communication of Tactile data. However, this can't be supported by current cellular systems as their protocols require too much communications overhead for synchronization, channel allocation, and mobility/connectivity management. Therefore, a new (5G) set of standards beyond 4G LTE is needed. Focusing on improving the wireless latency is critical to designing next generation networks. A one way transmitter- to-receiver delay limit of 0.1 ms requires changes in network layers, for example by minimizing transmission time intervals and increasing the bandwidth of radio resources. In addition, to reduce processing delays at the receiver, a redesign of the physical channel structure is necessary. As packets pass through all protocol layers delay is added at every step. The Medium Access Control (MAC) layer must distinguish Tactile data from other data types and provide mechanisms to eliminate collisions for quicker medium access.

On the other hand, the integration of mobile edge cloud with the base station is sufficient to keep latency below 0.5 ms. Backhaul and storage latencies depend on distance, equipment and protocols (to be discussed in chapter 6). Finally, Tactile data are produced from sensors at a constant rate, so keeping packets small helps the encoder/decoder to fast process and transmit to next device. This requires reducing the headers and control bits. Generally, a tradeoff between processing delay and transmission delay is important in order to determine the best outcome combination.

5.2 Reliability

Current research in wireless communication has been driven by the need for increased throughput. Indeed, 4G LTE has brought transmission rates of 50 Mb/s or higher. However, to be able to provide mission critical services to applications such as in transport systems or industry automation (discussed in previous chapter), an ultra-high availability is required. It is closely related to latency since different percentages of reliability can be guaranteed over flexible latency requirements.

Reliability is the probability that a packet is transmitted successfully in a network and the total performance of the link is above a certain latency level. For example, a reliability of 99. 99% means that a packet in 1000 is expected to be lost. Simulation experiments as well as real life data are used to determine availability and the annual outage time.

Availability issues are caused by atmospheric conditions and multipath propagation. Because 5G is going to utilize the spectrum band of up to 100 GHz, this means that rain, for example can be a negative factor in signal attenuation at the receiver. When the wavelength is the same as rain drops it can cause problems. Multipath propagations occur when two or more copies (of different paths) of the same signal arrive with a time shift at the receiver. If the signals are out of phase then they may cancel each other and result in destructive interference. So the terminal has to wait for the transmission channel to change to be able to receive data.

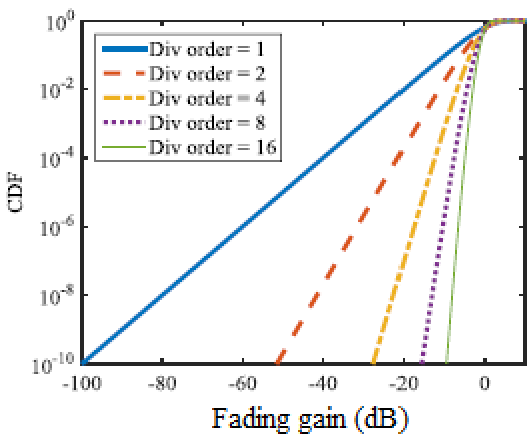
The most stringent requirement on reliability on 1 ms latency is factory automation where 1 in a billion packets may be either lost or erroneous or arrive too late. A question that then arises is how ultra- high reliability can be guaranteed in wireless communications.

The most powerful tool in the physical layer to achieve high reliability communications in a fading channel is Diversity. It is the ability to take advantage of channel variations in time, frequency and space [6]

Progress in the spatial diversity can be achieved by increasing the number of antennas in base stations (BS) and receivers .Diversity can also be achieved using resource blocks of independent fading coefficients in frequency or using time slots in time diversity. There is a significant cost in guaranteeing ultra- high reliability. The first is by increasing the power of a single link of one BS and the second is by employing several power links to one or more BS. The latter has been a hot research topic for two reasons:

1. It is feasible to guarantee reliability with more links using low power transmissions instead of raising the link budget of a single link either through power increase or more efficient coding. Reliability metric is covered by the conditions that at least one link transmits continuously.
2. Achieve a performance gain in the receiver side through simultaneous processing of the same signal coming from different links.

For wireless communications, to measure the effect of a propagation environment on the radio signal, the statistical model of Rayleigh fading is used. The cumulative distribution functions (CDF, vertical axis) of fading gains (horizontal axis) in Rayleigh fading channels of various diversity orders is shown in Picture 15. It can be seen that an increase in the diversity order reduces the dB margin needed to eliminate fading gain.



Picture 15: Fading gain (dB) (source: Ericsson Research San Jose, California, USA)

For example, fading gains of up to -90 dB happen with 10^{-9} probability for diversity order equal to 1.To guarantee reliability higher than 10^{-9}, a 90 dB margin is needed to eliminate outage due to fading. Similarly, increasing diversity order to 4 would lead to the reduction of the needed dB margin to 27 in order to keep the same bit error rate.

It is possible [9] to determine the optimal number of links with respect to power consumption to achieve any desired high reliability. In general to double the number of nines in reliability, (ex from 99.9 to 99.9999) it is optimal to double the number of links. However the interference effects should be carefully examined to limit deviations from those figures.

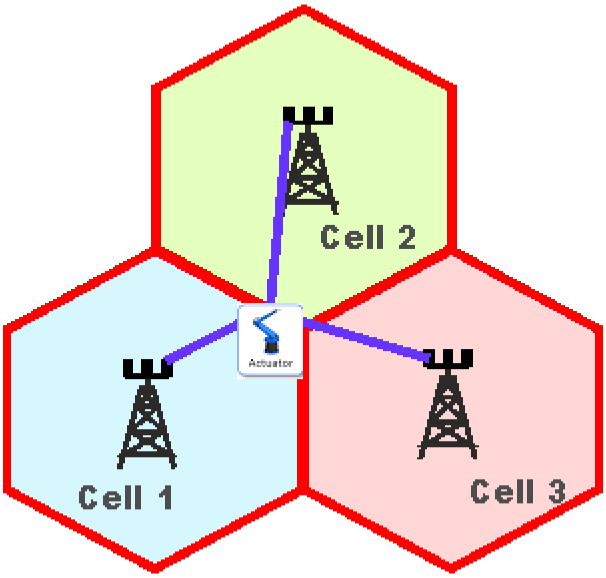
Every possible use case scenario must be analyzed for optimal diversity implementation. For example in a factory automation, implementing an ultra- high reliability wireless solution would require simulation experiments with varying parameters such as factory area, number of base stations, links per base station, clients, coverage factors, bandwidth, packets size (10 bits to 1000 bits), coding techniques, modulation and fading model.

Furthermore, Coordinated Multipoint Connectivity (CoMP) (Picture 16) based on the diversity parameters discussed above could be a potential solution to satisfy the reliability requirements of Tactile Internet. CoMP has been the focus of many studies by 3GPP (3rd Generation Partnership Project) for LTE-Advanced and IEEE for WiMAX (Worldwide Interoperability for Microwave Access).

The advantages of CoMP in LTE Advanced for users and providers:

- Makes better utilization of network: By providing connections to several base stations at once, using CoMP, data can be passed through least loaded base stations for better resource utilization.
- Provides enhanced reception performance: Using several cell sites for each connection means that overall reception will be improved and reliability will be increased.
- Multiple site reception increases received power: The joint reception from multiple base stations or sites using LTE Coordinated Multipoint techniques enables the overall received power at the handset to be increased.

- Interference reduction: By using specialized combining techniques it is possible to utilize the interference constructively rather than destructively (especially at the cell borders), thereby reducing interference levels.



Picture 16: Multipoint Coordination in LTE

The usage of diversity, discussed in [8], showed that it is possible to obtain the required reliability and latency requirements by providing sufficient radio resources. Very high availability of coverage can be guaranteed by analyzing dependencies between the required bandwidth and antenna configuration on one side, and latency, reliability or interference power level on the other side.

Similarly in [7], to ensure the QoS of Tactile Internet in a vehicle collision avoidance scenario, an optimization of bandwidth allocation is required. A tradeoff between maximal transmit power, bandwidth and the number of transmit antennas is necessary to guarantee the ultra-low latency and reliability requirements.

As a conclusion, it is possible to guarantee Tactile Internet QoS in controlled simulation environments. However, further research is needed to evaluate metrics such as delay and interference in real life conditions.

5.3 Security

Security and Privacy are also the important parameters for the Tactile Internet. As Tactile Internet will operate (mainly) under the 5G ecosystem, its security requirements have to be included in the steps towards 5G standardization. On the other hand, 5G must provide variable security at the network access level and at the service level depending on each specific use case.

A general picture of what new characteristics might next generation wireless networks introduce is given below (Picture 17).They are all expected to shape our actions on providing security and privacy:

1. New trust models – new business models, new players, different security requirements
2. Security for new service delivery models – virtualization and softwarization of networks
3. Increased privacy concerns – latest cases of massive surveillance programs (NSA)
4. Evolved threat landscape – broad range of infrastructure depending on new technology

Picture 17: (Security in 5G) source: ericsson.com

Security is a complex issue that depends on many parameters which should be carefully examined during Tactile Internet communications.

How strong security is provided depends on how frequently communication occurs, the amount of data to be handled and communicated, speed and latency and around how frequent authentication has to be. For example, mission critical communications will require much more frequent authentications than IoT and will involve more sensitive data as well. As performance demands will increase, highly efficient security mechanisms will emerge. It is clear that the security challenges for Tactile applications cannot be met by existing technology.

The three building blocks of security are confidentiality, integrity and availability. Different security requirements of these blocks have to be implemented on different layers of the system which can be distinguished in:

- Network access security
- Network application security
- Service Layer security
- Authenticity, integrity and confidentiality of data transmitted at different network layers

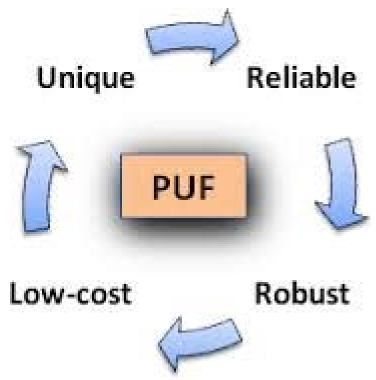
As new technology will bring new services and applications and include massive numbers of networked devices, so will threats evolve to a new level challenging the resistance of the system. New security threats and a large potential attack field will put pressure on the latency metric of Tactile Internet. Because 5G itself will be a critical infrastructure like energy or water supply, any malfunction will have cascading effects.

Next generation networks will support public transport, healthcare, smart grids with cloud-driven robots in automated factories and augmented reality. Major players will come from public service providers, Mobile Network Operator (MNOs), device manufacturers, infrastructure providers and chipset providers.

This technology will provide different security requirements at the access and service layers – identification, enrollment, message authentication and non-repudiation, data integrity and key and identity management. Several layers of security may be required, depending on the use case and the type of communication (device- to- device or device-to- network) and the result may be a diverse and complex security infrastructure.

Breaches or man-in-the-middle attacks in use cases such as, connected vehicles, remote surgery, public safety and first-response networks would be catastrophic to the image of any company or public organization deploying such technologies and therefore security must be treated with extreme importance in the above area. Appropriate certification and qualification will therefore be important in many of these use cases.

Data is likely to include geolocation data, instructions to elements in cloud based interactions and medical, operational and situational data. Some of this data will be highly sensitive and will be communicated more frequently than in other 5G segments.



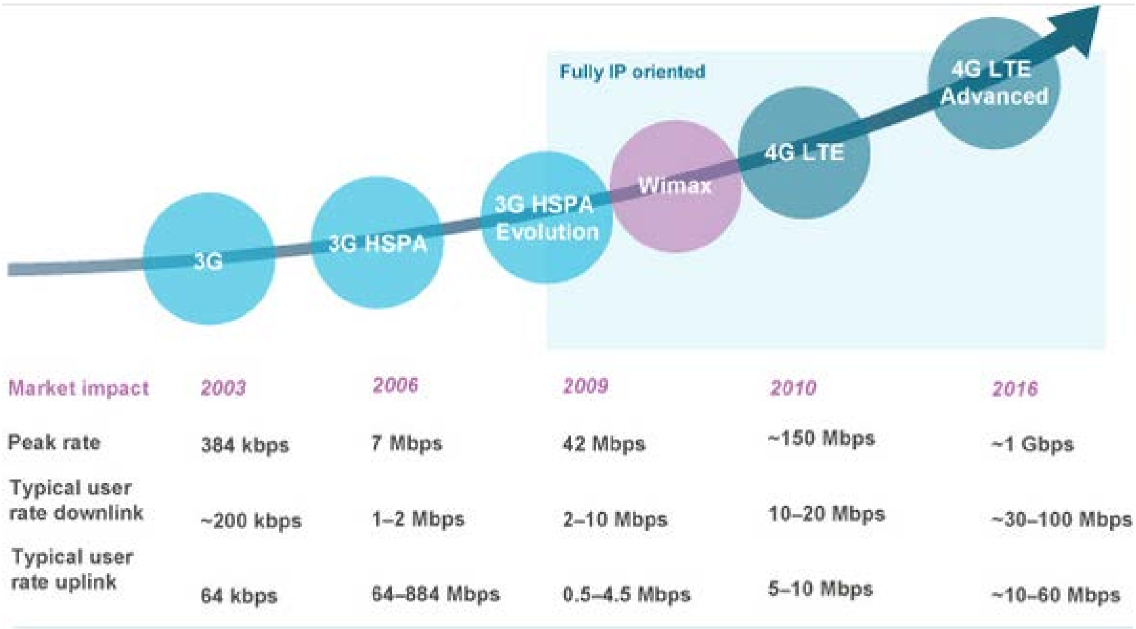
Picture 18: Physically unclonable functions (PUF) (source: rijndael.ece.vt.edu)

Managing network connectivity securely will require advanced hardware elements such as HAEC boxes (discussed in chapter 1) and associated servers to initially securely provision credentials. Privacy management, group management and user and device authentication will be needed to manage identities on the network. To meet latency expectations, security should be included in the physical transmission. Cryptographic overhead must be kept low to avoid extra latency such as additional headers, key exchanges, synchronization frames and special attention must be given to the Tactile edge. Furthermore, with the increase of computational power, attackers will have an important weapon, so an analysis of available cryptographic solutions should precede the correct selection of security tools available. So to introduce a low delay identification system at the receiver side, the usage of either specific hardware such as Physical Unclonable Function (PUF) (Picture 18) for cryptographic key generation and device authentication or biometric fingerprints is necessary to meet the high security requirements.

5.4 Links throughput and capacity

4G LTE Advanced currently provides links of around 300 Mb/s in theory which practically translates to under 50 Mb/s (Picture 19). However, considering the Tactile Internet applications requirements, the speed must be upgraded to over 10 Gb/s.

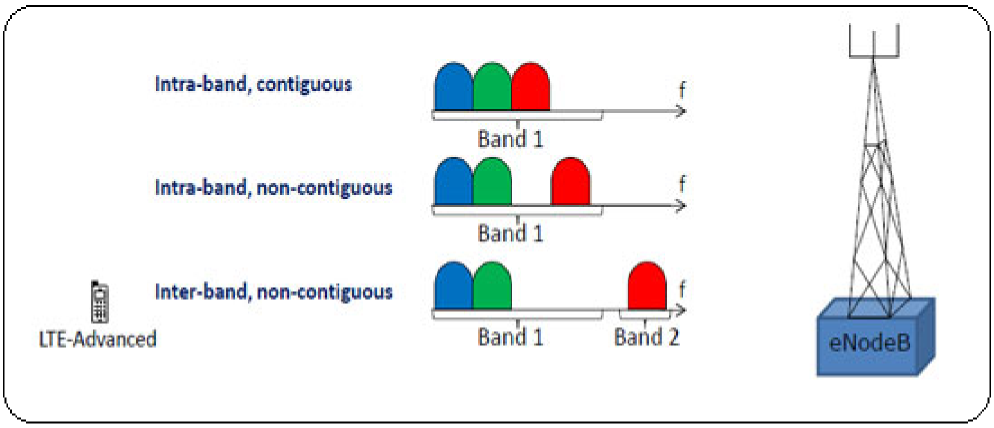
Data rate has been the main driver for wireless communications either in the licensed or the unlicensed spectrum. For 5G to be able to deliver rates of >10 Gb/s, which is what optical fibers provide, new enhancements of functionalities of LTE Advanced are required.



Picture 19 .Cellular throughput (source: Teliasonera)

Obviously, one way to increase capacity is to add more bandwidth. The most important and feasible techniques are:

a) Carrier Aggregation (CA) – This technology (Picture 20) increases the bandwidth of wireless connections by allowing a device to download (upload) data from multiple network bands at the same time. 4G bands are split up into data carrying slices that have a bandwidth of 1,3,4,5,10,15,20 MHz. Since up to five component carriers can be added together, the maximum bandwidth for a single link is 100M Hz. It works for both download and upload connections. CA works by aggregating carriers situated in the same band (intra-band, contiguous or non-contiguous) or different bands across different frequencies.



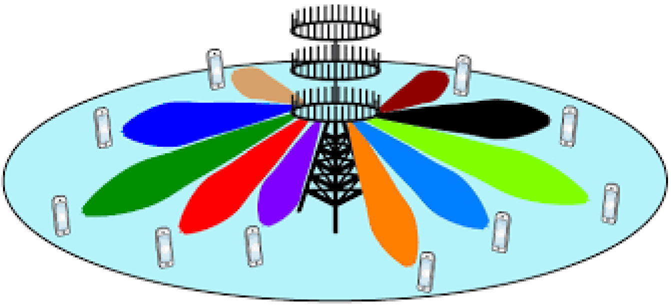
Picture 20(Carrier aggregation) source: 3GPP

Although commercial support up to 3 carriers with peak data rates up to 450Mbps, Tactile Internet will benefit from advances in 5G carrier aggregation techniques such as:

- Increasing the number of component carriers to 50 to support rates of >10 Gb/s bandwidth both in download and the upload.
- Support for a greater number of frequency bands and combinations of frequency bands.
- Using Carrier Aggregation between cells to enhance the support of small cells and Heterogeneous Networks (HetNets).
- Techniques of aggregation of TDD (Time division duplex) with FDD (Frequency division duplex) carriers since LTE Advanced CA supports aggregating of the same type.
- Extending Carrier Aggregation both in licensed and unlicensed spectrum.

Network operators and manufacturers are pushing forward especially in the TDD/FDD aggregation in order to take advantage of all available spectrum resources. This allows a dynamic configuration of both uplink and downlink rate based on traffic conditions. Backward compatibility can be provided based on carrier aggregation so that 5G devices can use 4G networks. Even forward compatibility can be possible so that older devices can access services on 5G networks.

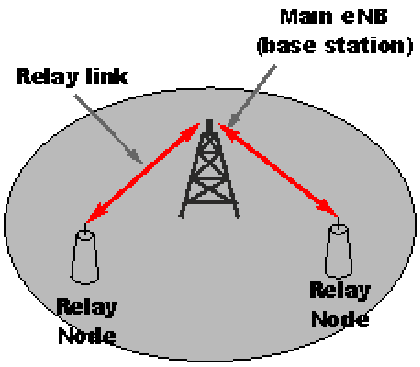
b) Massive Multiple Input Multiple Output technology (Massive MIMO) (Picture 21) is an enabler towards increasing throughput in next generation networks. Signals from multiple antennas can be combined to enhance data rate. These antennas are synchronized in phase and can focus the beamforming towards a single user instead of transmitting the whole coverage area. Therefore, larger number of antennas helps to reduce interference in other users. Efficient radio resource management is thus achieved by efficient use of frequency (and time) resources.



Picture 21: Massive MIMO (source: com msys.isy.liu.se)

With advances in technology antenna chips are expected to increase the numbers of inputs and outputs for simultaneous channel access. This approach has two advantages. First it does not require further investment in BS sites and hence backhaul support infrastructure. Second it improves the energy per bit ratio by 100 times or more.

c) Relay nodes – It aims to improve both capacity and coverage to prevent performance degrading at cells edge. Tactile and 5G services must also be available at cell edges (Picture 22). A feasible and low cost solution is the relay node which is placed at the edge and communicates wirelessly with the base station. It is a fixed node which operates without backhaul wire.



Picture 22: Relay Nodes

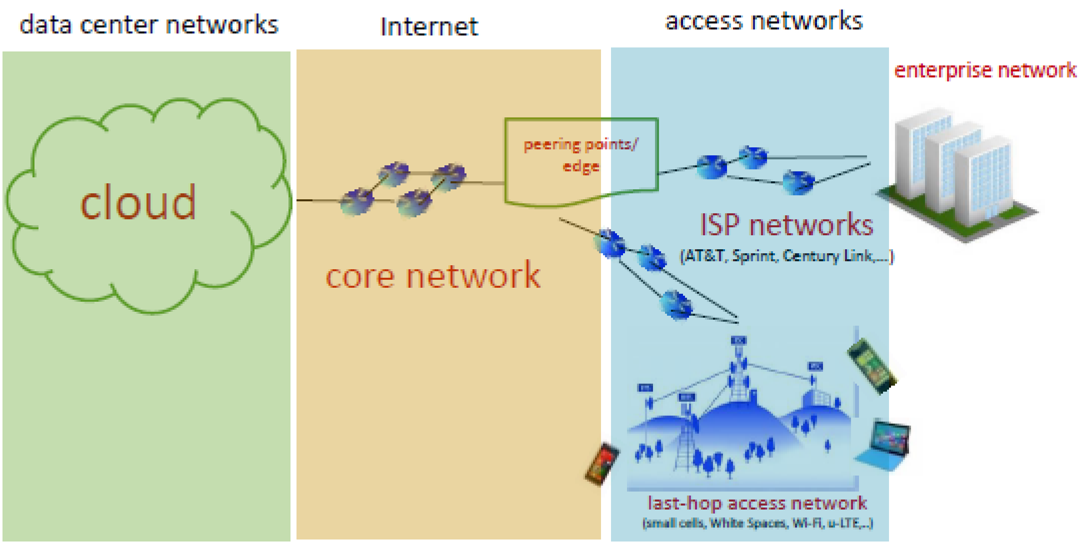
Because it demodulates and recodes data before retransmitting, it adds delay. However because of their small size they are convenient and ensure good signal is received by all users. Other than improving capacity, it can extend coverage and provide the basis for future BS implementation. On the other hand they increase network complexity when compared to single hop communication.

6 Infrastructure elements

Core Network technologies and cloud networking are of equal importance to realizing the vision of Tactile Internet. The combination of a relatively robust wired with a wireless medium raises challenges for researchers on rearranging network functionalities to meet its requirements.

6.1 Core Network (CN)

An important factor in the Tactile Internet functionality is the Core Network (Picture 23). The reduction of network nodes is obviously necessary to keep latency low because every node adds overhead. It can be achieved by pushing some of its functionality at the edges or Radio Access Network (RAN). Software defined networking and network functions virtualization (discussed in the next section) can offer the network functionalities on demand required for Tactile Internet services. An important factor that increases latency is buffer queue in network switches. For the IP network protocol (or IPsec for security) the queuing time varies significantly, sometimes making the data of late arriving packets useless because of increased end- to- end delay. Another factor is packet loss as a result of buffer overflow in the switches. Techniques that correct the errors, like TCP error correction mechanism, add to latency. So to guarantee a maximum delay a reservation of end- to end resources is necessary.



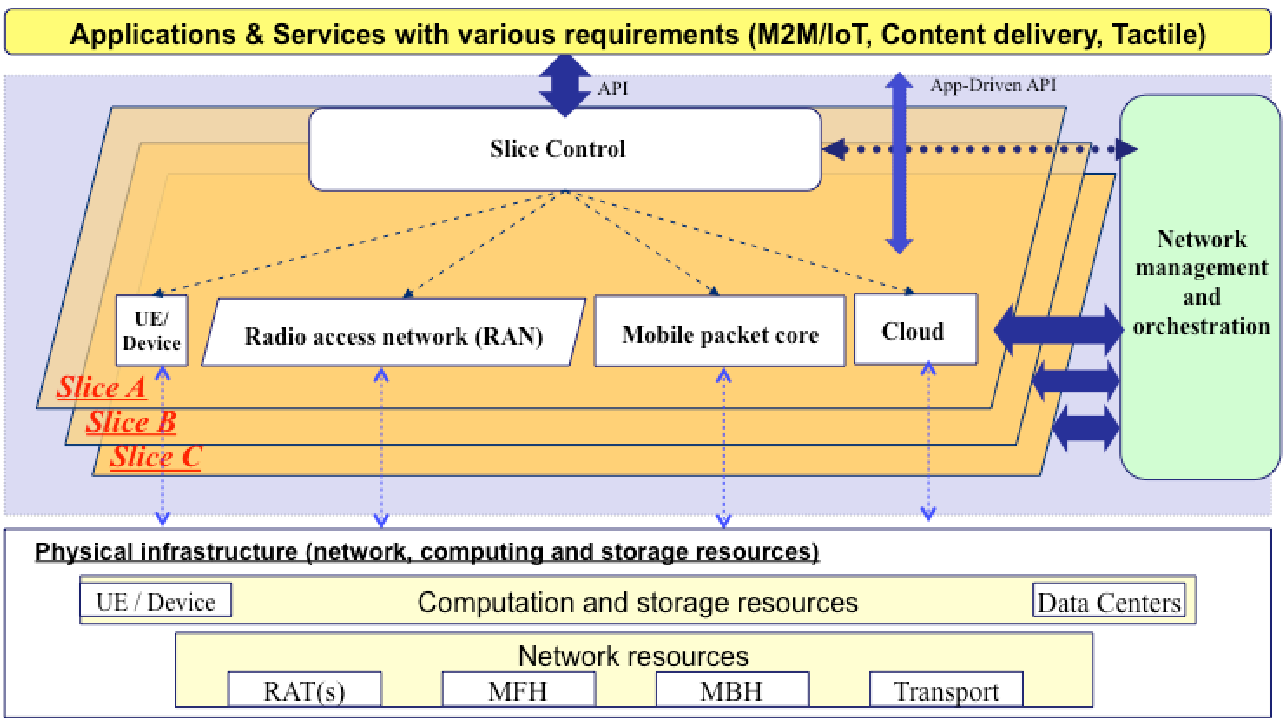
Picture 23: Contributors to latency (source: Microsoft)

Almost zero queuing times could be achieved by network scheduling and synchronization along the path. In general, making networks less complex (opposite of what we are doing today) and providing the protocols suite that cover the specific environment of Tactile Internet will deliver a good predictable performance. For example, it is better to design a lightweight network protocol for Tactile data than to add latency through header compression techniques.

Furthermore, complexity exists because there is actually no control on data routing. Each ISP controls a number of Autonomous Systems (AS) and their peering agreements are so sophisticated (dictated by finance and politics) that performance prediction is not possible. Routing policies must be revised for faster data forwarding based on packet size (small for Tactile data) and type of service.

6.2 NFV, SDN

5G networks will support a broad range of services and applications such as IoT and Tactile Internet, as discussed in the first chapter. Standardization bodies have not reached a consensus on an architecture yet. However, because of the different nature of its applications and higher services complexity, most researchers seem to converge to the separation of hardware infrastructure from the logic.



Picture 24: Network softwarization view of IMT-2020 mobile networks (source: ITU)

5G should be fully flexible, hosting vertical industries applications into a common hardware infrastructure. Terms such as network on demand [3] or softwarization (Picture 24) of network [12] reflect to some extent the transformation of telecommunication architecture.

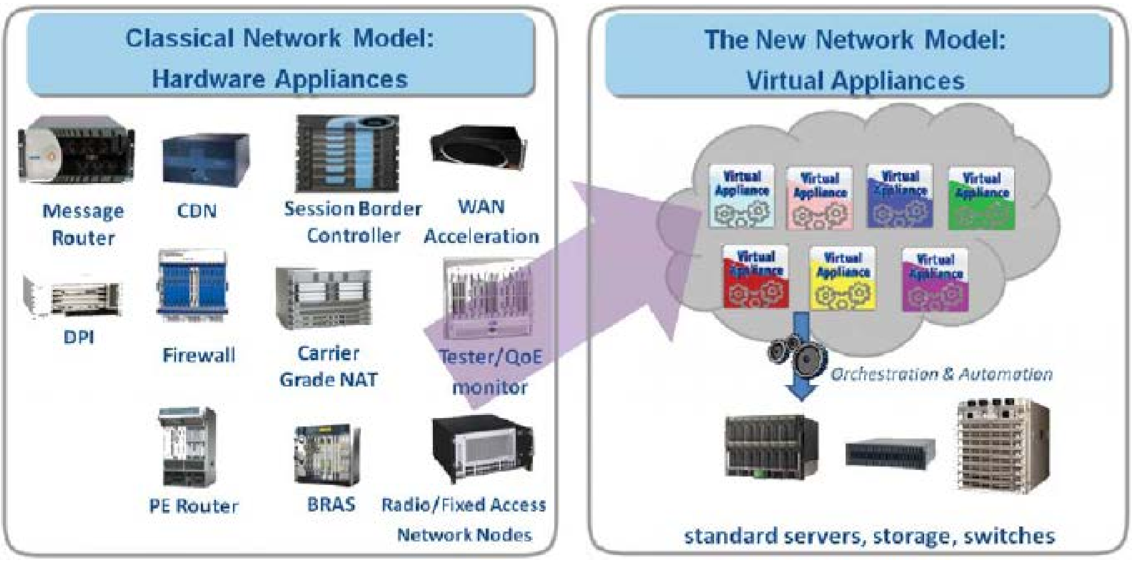
Recent trends in Network Function Virtualization (NFV) and Software Defined Networks (SDN), along with Mobile Edge cloud Computing (MEC), are considered the main enablers of improving QoS of telecommunications. Some advantages of NFV in general are:

- Low cost
- High flexibility
- Scalability
- Security
- Location independent (globally)

There are increasing difficulties for new service domains and players to enter the market and reach potential users. It is not easy to always adapt to the existing range of network hardware equipment due to manufacturers restrictions on flexible configuration. So NFV and SDN have come to eliminate those problems. NFV changes the way how network operators design their infrastructure by means of separating software from hardware platform (Picture 25). Therefore they have a direct impact on services and applications. Lately there have been encouraging results translated in high performance and lower costs, through the implementation of (not only) open source frameworks. So, in the future a full decoupling of network functions and services from hardware (servers, switches and storage) will be the main trend. The former is expected to run on virtualized machines and execute commands on the latter. These software modules can be run as needed, using existing hardware, hence the term network on demand.

As an example, consider the Cyberoam unified threat management solution provided either as hardware equipment or as a software platform running on a virtualized machine. The latter can be implemented on different hardware (switch, modem) and still provide guaranteed performance, reliability and flexibility.

Recent trials have also [13] demonstrated that it is feasible to implement network functions on general-purpose processor-based platforms, for example, for physical layer signal processing and components in cellular Core Networks.



Picture 25: Dedicated Hardware vs NFV (Source: globaltelecomsbusiness.com)

NFV is closely related to other related technologies like SDN. Software defined networking is a networking technology that separates control from data planes. It is changing how we design and operate networks. With SDN, networks are transformed into programmable pieces of the cloud infrastructure. Control and monitoring is thus possible, providing customization and optimization.

Its ability to direct and automate traffic makes it easier to implement QoS for Tactile data. Issues such as security and availability can be handled successfully by SDN while accessing the network infrastructure. The key advantage is the possibility of running control commands in data centers that are decoupled from traffic flow. This is possible even by using application programming interfaces (API).

SDN is complementary to NFV and they have the power to improve telecommunication metrics. Virtualization of parts of mobile Core Network, for example, can scale up and down the services offered on demand. It enables flexible distribution of hardware resources to maximize performance and rapid instantanization of innovative Tactile services. Both NFV and SDN were initially proposed for data center services leveraging and a transformation of Internet content delivery. Their use in mobile Core Networks guarantees the closing of the loop in Tactile applications. Not only the Core Network but also the radio access network can move towards softwarization. Network abstraction and control of data commands creates flexible virtual communication channels that can achieve both high throughput and reliability on latency constrained scenarios.

The introduction of an operating system situated at the mobile edge will transform the latter to powerful software platforms enabling the anything as a service (xAAS) vision . A use case scenario in [12] with a prototype showed that it is possible to provide low end- to- end network and application latencies. Challenges remain however, for NFV to at least meet the performance output of dedicated hardware and to a lesser extent to offer a smooth migration to the new design.

According to the ETSI NFV Industry Specification Group and its footprint on the Tactile Internet ecosystem the technical challenges include:

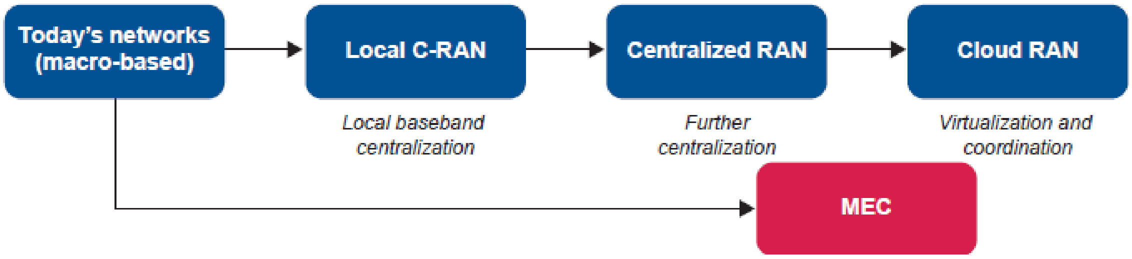
1. Achieve coexistence with proprietary hardware- based network platforms while enabling an efficient migration path to fully virtualized network platforms which re-use network operators BSS and OSS.
2. Management and orchestration of virtual network appliances while ensuring security from attack and misconfiguration.
3. Maintain network stability and service levels without degradation during appliance load and relocation.
4. Ensure the appropriate level of resilience to hardware and software failures.

When these challenges will be met, there will be more room to discuss about one more enabler technology for Tactile applications.

6.3 Mobile Edge Computing

According to ETSI, Mobile Edge Computing (MEC) is a new technology which is currently being standardized in an ETSI Industry Specification Group (ISG) of the same name. It has been setup by Huawei, IBM, Nokia, Intel, NTT DOCOMO and Vodafone and more than 28 companies have joined the effort to create an open standard. Mobile Edge Computing provides an IT service environment with cloud-computing capabilities at the edge of the mobile network, within the Radio Access Network (RAN) and in close proximity to mobile subscribers. The aim is to reduce latency, ensure highly efficient network operations and service delivery, and offer an improved user experience.

It complements both NFV and SDN towards the development of next generation networks. MEC (Picture 26) was proposed in late 2014 as the solution to overcome the problems of providing sufficient quality performance of end users. While NFV virtualizes network functions, the MEC platform enables applications to run at the edge of the network.



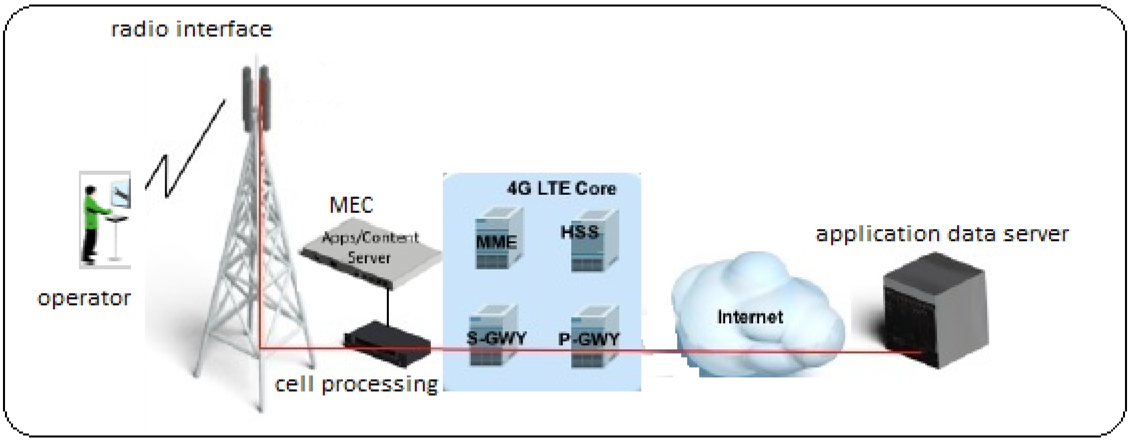
Picture 26: MEC deployments may be built upon existing C-RAN or Cloud RAN infrastructure and take advantage of the backhaul links that have been converted from legacy to these new centralized architectures. (source: Ovum)

For the network operator, the benefits of MEC focus on the following:

- High ROI as it differentiates the classic role of the network from a medium channel to a strong binding between the content providers and the network itself. It makes it easier to entering market for new companies providing digital products.
- Use data analytics at the edge to increase customer overall experience making use of location- based services as well as high throughput and low latency.
- Ability to support M2M and Tactile applications by shifting virtualization towards the edge to ensure that QoS requirements are met.

While base stations just forward traffic, MEC (Picture 27) introduces powerful IT servers and equipment that analyzes and gives feedback on user requests. In this way it is possible to manage traffic directly at the mobile edge by adding some decision-making services, instead of forwarding it to the remote data centers. It is inevitable that a change in the cloud mode infrastructure will lead to a highly decentralized architecture with mobile edge computing and cloudlets.

A high performance edge server is one of the keys to reducing the latency in the mobile network. When packets do not have to travel through the Core Network to the datacenter, an application can provide real time services with low end- to- end delay. Tactile applications can be supported only when MEC architecture itself does not introduce considerable delay in signal processing.

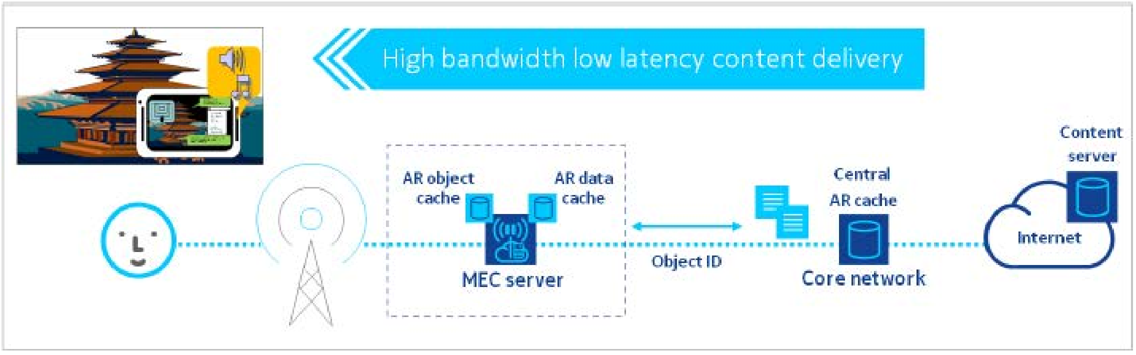


Picture 27: MEC integration in the base station

Resource hungry Tactile applications can benefit especially from the following MEC application classes:

- Edge Content Delivery
- Offloading
- Aggregation
- Local Connectivity
- Augmentation
- Content Scaling

So it makes sense to use wireless bandwidth to offload Internet and Core Network bandwidth because it is much higher. From a technical perspective users take advantage of reduced communication latency and data centers from traffic relief. The network latency can furthermore be reduced by using traffic steering techniques and prioritization at the radio site. Latency-sensitive Tactile data are identified by techniques at the scheduler level and directed to the application server more quickly than other data.



Picture 28: Augmented reality application scenario (source: ETSI)

For example, let’s analyze the task of an augmented reality app on a user device that includes real time data computation (Picture 28). These services require location data and movement patterns in order to analyze and provide additional information to the user. Instead of being processed on a user device, it can be perfectly performed on the edge saving both battery and computational power while benefitting from increased speed in edge processing. User mobility must be supported in order to experience uninterrupted content.

a) By having access to radio network management, the application at the server-side can benefit from real time information from the radio access network (for example, what is the dedicated bandwidth of the client or what the number of total users inside the cell is). This information may be used to introduce machine learning techniques and adapt accordingly to future service requests. More specifically, a tradeoff between the number of users and the bit rate that each user enjoys, is what edge computing could do to provide optimal experience.

b) Very low responsive times. This is extremely important for Tactile Internet applications where every layer adds its own piece of latency. The integration of the content and network functionalities in a ‘box’ may lead to the so called thinning of the network.

It is not feasible to deliver these services from cloud since the information is location specific and is bound to a particular MEC server. Therefore it is irrelevant to provide the same services as some MECs provide.

As for security issues, keeping application server close to the base station limits the security implications while increasing profit for all involved parts:

- Consumers (Increased quality of experience)

- Software developers (Gain network information)
- Network operators (Host application servers)

The alignment with emerging distributed cloud approach makes MEC an important building block of 5G and a Tactile Internet services enabler. However, there are issues to be resolved by standardization bodies such as:

- The network operators lose some control over the applications. Although security issues are limited, physical security still remains a challenge. Malicious behavior may compromise the whole system.
- There will be an upper bound on the MEC computation capabilities with some use cases overloading the system. Similarly, as for throughput and latency, possible implications with backhaul and inter- access point links, may influence real time communications.
- There is a problem with mobility support. The small cell concept limits the range of connectivity. For example, the distance of a user from MEC increases, so does the latency metric. This worsens the overall experience. So how do you keep connectivity with a distributed cloud approach from your new location? A solution could be the installation and deployment of virtual machines on demand.
- Management and orchestration of APIs in a highly heterogeneous hardware and software environment.

I believe that MEC will play an increasingly important role not only in providing the critical requirements of Tactile applications but also in reducing cost of mobile services.

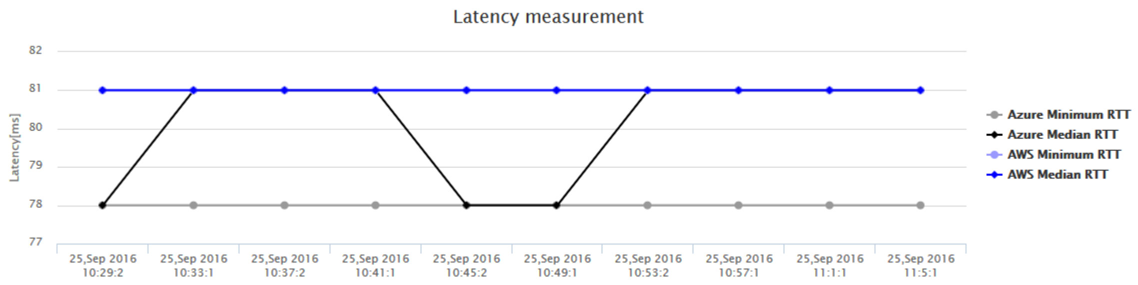
Until now there has been a theoretical discussion about MEC infrastructure in wireless networks. To my knowledge there has not been a real world implementation except from NOKIA (19 September, 2016 Nokia launches Mobile Edge Computing-based enterprise applications).

Mobile Edge Computing (MEC) allows enterprises to take advantage of the latest generation LTE technology, in particular small cells, and real time applications for building complete campus networks. These networks meet the demanding privacy, resilience, and latency requirements set by business-critical applications, extending LTE to new domains.

6.4 Cloudlets

A related approach similar to this system is the mobile cloud computing, or otherwise cloudlets. Cloudlets are the enabling technology for a new range of highly desirable but latency-sensitive mobile applications that will emerge in the next generation networks. These include new augmented reality applications that will transparently enrich a user's ability to interact with the environment.

By default, a cloud center runs services that are crucial to mobile devices. Because clouds are large centralized data centers, the distance between the user equipment does not allow for low latency applications (Picture 29). A growing number of hops, network layers, threat management systems and firewalls results in high latency.



Picture 29: Azure Cloud latency (claudit.feld.cvut.cz/rtdata.php)

```
C:\Users\julian>tracert -d  213.189.188.3

Tracing route to 213.189.188.3 over a maximum of 30 hops

  1     1 ms     1 ms     6 ms  192.168.0.1
  2    24 ms    22 ms    25 ms  62.169.255.87
  3    23 ms    24 ms    27 ms  62.169.247.205
  4    34 ms    35 ms    33 ms  62.169.252.97
  5    32 ms    34 ms    33 ms  62.169.249.174
  6    34 ms    36 ms    33 ms  63.218.173.153
  7    76 ms    73 ms    74 ms  63.223.13.138
  8    86 ms    88 ms    87 ms  130.117.14.233
  9    73 ms    75 ms    72 ms  130.117.48.114
 10    95 ms    92 ms    91 ms  130.117.0.141
 11    84 ms    82 ms    86 ms  154.54.59.58
 12    87 ms    86 ms    86 ms  154.25.1.250
 13    90 ms    88 ms    86 ms  149.6.135.250
 14    85 ms    87 ms    85 ms  212.68.211.154
 15     *        *        *     Request timed out.
 16    91 ms    89 ms    90 ms  212.68.215.114
 17    87 ms    86 ms    86 ms  213.189.188.3

Trace complete.
```

Picture 30: Google Cloud latency in Europe

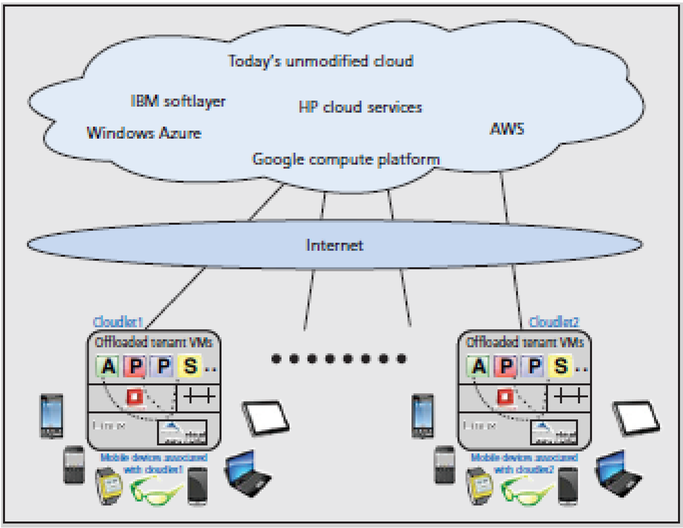
Especially WAN (Wide Area Network) introduces latencies that are impossible to get low with the existing architecture. Typical values of RTT (Round Trip Time) delay times of existing commercial cloud systems are in the order of 75-85 ms (Picture 30). Rather than focusing on improving latency, service providers keep pushing for higher bandwidth. Apparently to bring the services closer to the users, the vision of cloudlets is introduced.

The process of bringing the cloud closer to the users creates the vision of Cloudlets (Picture 31) which belong to a 3 tier hierarchy according to Elijah Gabriel. They are located just a hop from the mobile device and can be regarded as a small data centre which can actually couple cloud services with the user devices.

According to the him, the characteristics of a cloudlet comprise the following:

- No hard state: It is mainly soft state and may contain cached state from the cloud or generated locally. It may also buffer data originating from a mobile device (such as video or photographs) en route to safety in the cloud. Extensive use of caching allows for almost zero management despite their highly distributed area.
- Powerful, Gigabit connections and safe: It possesses sufficient compute power (i.e., CPU, RAM, etc.) to offload resource-intensive computations from one or more mobile devices. It has excellent connectivity to the cloud (typically a wired Internet connection) and is not limited by finite battery life (i.e., it is plugged into a power outlet). Its integrity as a computing platform is assumed; in a production-quality implementation this will have to be enforced through some combination of tamper-resistance, surveillance, and run-time attestation
- Close at hand: It is logically proximate to the associated mobile devices. "Logical proximity" is defined as low end-to-end latency and high bandwidth (e.g., one-hop Wi-Fi). Often, logical proximity implies physical proximity. However, because of "last mile" effects, the inverse may not be true: physical proximity may not imply logical proximity.
- Builds on standard cloud technology: It encapsulates offload code from mobile devices in virtual machines (VMs), and thus resembles classic cloud infrastructure such as Amazon EC2 and OpenStack. In addition, each cloudlet has functionality that is specific to its cloudlet role.

It is clear that both latency and throughput of one hop outperforms the end- to- end performance of the cloud. Tactile Internet applications such as traffic optimization and augmented reality can benefit by bringing the cloud closer to the mobile user.



Picture 31: Cloudlet vision (source: Satyanarayanan2015)

Devices connect to the nearest cloudlet and use its services for offloading purposes mainly. Cloudlets keep connectivity with cloud system but this does not fall into the latency constraints of the user-cloudlet communication. They provide the reliability and availability required in case of cloud general failures or attacks. Rather than being managed by network operators (as mobile edge computing), cloudlets are operated by mobile end users. Cloudlets find implementation in LAN areas where user devices connect by WI-FI and benefit from increased computational power. Therefore the main difference between cloudlets and MEC is that the focus target of cloudlets is some specific user devices while the focus target of MEC is all user devices. The other is that MEC are situated close to base stations and serve accordingly a large number of user devices.

The impact of cloudlets on interactive mobile cloud applications has been theoretically discussed in research community. Although there is no real world implementation, the characteristics of caching and transferring content of cloudlets make them important in video streaming and file editing. The introduction of interconnected cloudlets will potentially ensure that a mobile IaaS is possible using cloudlets approach and cloud-cloudlets connectivity. In addition, wireless routing protocols could be proposed to realize the D2D communication and the inter-cloudlet connectivity. Furthermore it is agreed that there should be performance gains in using cloudlets in system throughput and data transfer delay. Tactile Internet applications can benefit from the one hop mobility scheme of cloudlet infrastructure.

The challenges that remain to be solved are similar with those of MEC. As resources in the cloudlets are limited, chances are that when a large number of users compete for resources, availability may not be guaranteed. A solution could be to give priority to mission critical parts of an application and forward other application components to cloud infrastructure.

Fog computing

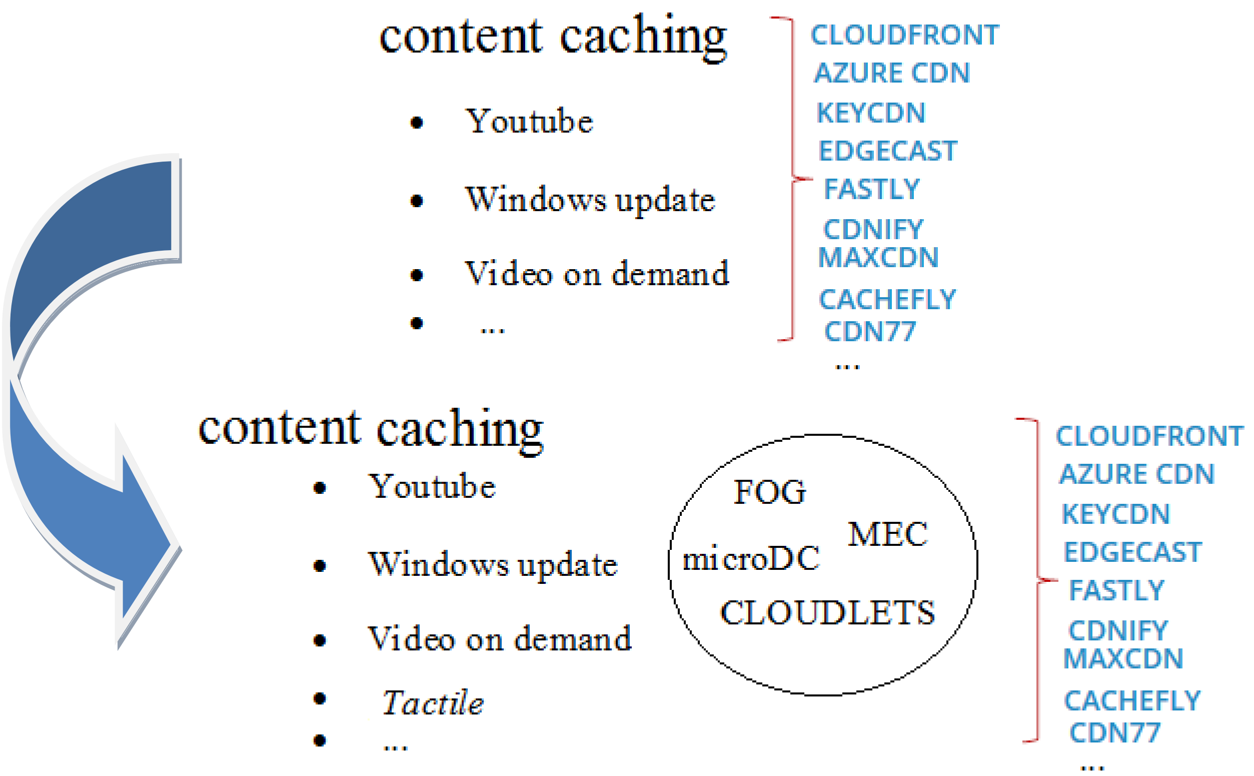
A similar approach to bringing the cloud closer to the user is through the implementation of fog nodes, a technology envisioned by Cisco. Similar to cloudlets, it is the middle part of a 3 layer hierarchy. A highly distributed infrastructure of fog computing nodes is within a few hops away from user devices. Software running on these nodes enables applications to run with low latencies. Its basic characteristic is the support for billions of devices through a fog network composed of computing nodes in all network levels for example on routers, radio access network. It is mostly intended to support the needs of IoT but Tactile applications with audio/visual feedback can benefit from the offloading and computational services hosted on these nodes. Tens of thousands of these computing devices will extend the cloud to the edge of networks. The use cases from chapter 3 that will most benefit are the connected vehicles smart grid applications and robotics for remote assistance. Interesting however is the ability of fog computing to close the loop of Tactile Internet applications where high precision and stability is required. This comprises both low latency and its small variations over time.

A comparison between fog computing, cloudlets and mobile edge computing is well documented in [15] where all these cloud extenders compete for their upcoming market share.

6.5 Caching and Artificial Intelligence

Tactile Internet applications will run on highly distributed cloudlets infrastructure and new caching techniques will need to be developed to keep latency low and jitter predictable.

Most content based Internet services today (Picture 32) are already provided on CDN (Content delivery Node) nodes whose main characteristics include improving the performance of search engines, deliver audio/video content, offload Core Network and enhance general user experience. Caching engines of tomorrow will reduce the closed loop delay. The most popular Tactile activities such as remote health diagnosis or remote servicing in industry will be kept in cache and help simultaneous Tactile interactions taking place through the same nodes. Tactile content preloading may take place even in a cloudlet node without previous knowledge of networks performance. Advanced algorithms will manage to stabilize the oscillations in latency in the new session.



Picture 32: Tactile content caching in the future.

Techniques for traffic prediction and hence caching mainly to decongest networks during peak hours are already an object of research. Combining of what the users request with what the network has to offer allows the network to make proper decision on predicting allocation resources. Reserving network resources for Tactile-aware applications in the context of caching is a step towards guaranteeing QoS for traffic with different requirements. This is particularly beneficial when many users request Tactile Internet services for the same application.

Besides proactive caching techniques at both Tactile Internet edges, research in artificial intelligence is necessary to break the limitations imposed by the speed of light. In this context, intelligent algorithms will speed up action at the robot side and feedback and reaction at the operating side. Tactile data analytics will improve the behavior of such algorithms and push the Tactile edges even further than a few kilometers. Obviously, the time for intelligence computing during Tactile applications must always remain within the 1 ms requirement and certainly, well under the ‘real’ (i.e. without implementing intelligence) interaction.

Machine learning systems will have preloaded patterns of Tactile data which are quite similar for specific use cases, for example force and torque in a high precision remote intervention has predefined action steps. Each step is the result of input data combined with cached intelligence to make reactions faster at the Tactile edge. Complex algorithms make decisions on the output as being real-data, predicted artificial ones or a mix of the two. Regression models can be prepared for Tactile specific use cases through supervised learning during the learning phase until a high level of accuracy is achieved which, for example, is especially important in healthcare. Therefore, predicted action must not only provide auto correction oscillation-free mechanisms but also help prevent damage at the actuator as the result of unintended wrong actions at the operator side.

Continuous increase in computation power and complexity of intelligent algorithms implemented in the cloudlet vision will be an important driver for the enhancement of Tactile Internet services.

7 Standardization

The process of Tactile Internet standardization is expected to take several years to complete. After that, the scale of adoption of the standards from interested third parties will outline its expected success.

7.1 Standards

Standards are documents that provide detailed specifications and predefined guidelines for products and procedures. They are important in ensuring that services and products are used in a safe and reliable way. The spreading of technological innovations through standards adoption helps companies to get into markets and achieve consolidation. Essentially a technological product's success is a complex issue and depends somehow on a family of standards. However, there might be several products that have the same functions and follow the same technical specifications, yet their success is different. Because a variety of products brings compatibility issues, standards' importance is critical to end users. They have the choice of using products from different vendors, yet, fully compatible with methods and activities workflow. Any step towards error minimization by implementing standards in every market chain, produces value growth for companies and product vendors.

A standard may be created for a specific issue and its range of adaptation depends on policies imposed globally, in several countries or even in large companies. In general it is not compulsory to use standards but their adaptation gives competitive advantage to interested parties. A major contribution of standardization in information systems is in reducing its complexity and ensuring interoperability. Standardization has been the key to driving economy not only in Europe but also globally.

There are more than 200 international standard development organizations that have that issued more than 500.000 technical standards. Collaboration between these standardization bodies is important to limit incompatibilities and enhance interoperability. These organizations' work is influenced by the following groups:

- Government bodies – The implementation of laws in market regulation is closely related to standards and how they are imposed by the lawmakers.

- Business companies – New opportunities are created in high tech sector that improve products and services through innovation.
- End users – Greater choice of quality products from a large range of companies. Consumers participate in the mass economy and enjoy enhanced functionalities as well as high equipment reliability.

The whole world needs standards and work is being done towards eliminating inefficiencies in areas where standards are inexistent. Examining the new communication and Internet technologies, competition between standardization bodies, particularly when patents are included, has become a major issue during standard specification process.

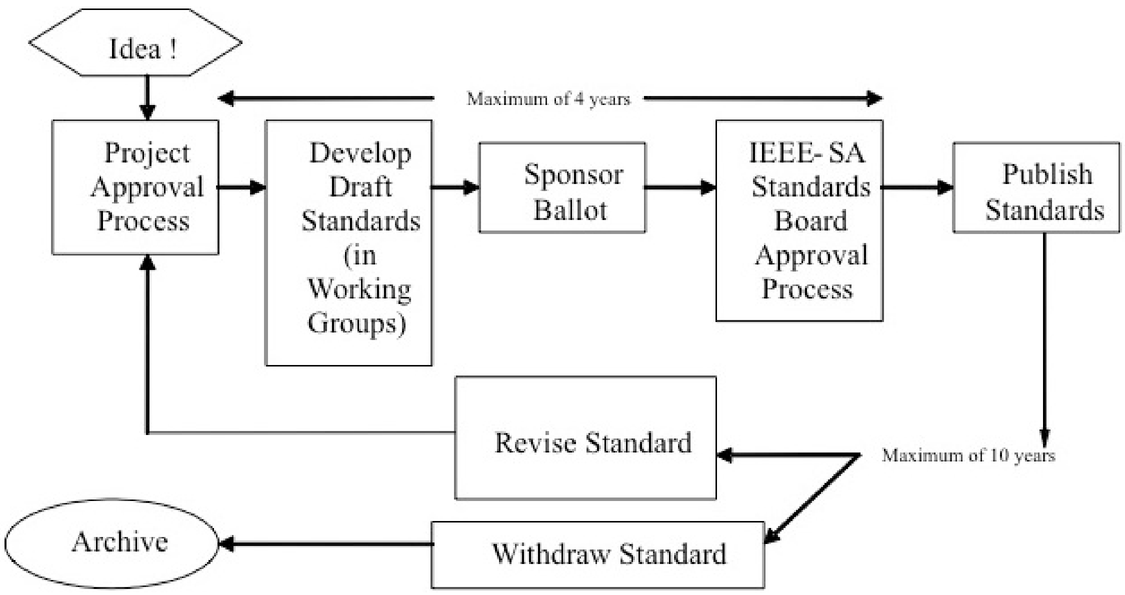
The role of Patents

The development of a technology standard almost always requires the critical contribution of several basic patents. Factors of innovation in these patents make their presence in the published standard a must. A simple smartphone can have for example more than 200.000 patents responsible for the technology used with several thousand belonging to IEEE 802.11 standard (Wi-Fi).

Therefore the challenges of standardization bodies for emerging domains like IoT or Tactile Internet remain continuous due to the high value business of patents. There are strict laws in western countries that define the rights of patent holders and outline the conditions on which a license may be issued. It is a global issue in the business and political context. It is common for patent holding vendors to charge expensive fees once their underlying technology has been assigned a building block of a standard. This might delay the introduction of new technologies because policies of most standardization bodies state that no global standard can be published if it's not preceded by granting of rights to patent holders. IEEE, for example, is being involved in 5G wireless standards and its interests are not fully aligned with patent holders of previous wireless generations. In general, the standard development and patent policy is a very complex issue resulting in years- long standard publishing procedure.

Standardization steps

Every standards development organization ensures that the standardization process undergoes strict rules that enable fairness and guarantee excellent results when compared to existing market values. A well-designed infrastructure of facilities, experimental platforms, guidelines, supervisors and working groups is dedicated to completion of the standard development process as well as its publication and continuous maintenance during its lifetime. The process is different with every standardization body applying its own procedure and choosing its own terminology although the result is similar with the competitors. The presence of both formal organizations (e.g. ITU, ETSI, IEEE) and non-formal (industry alliances), functions towards reducing standardization time process. IEEE (picture 33) standardization process for example (similar to other formal bodies) consists of a number of steps that lead to standard output.



Picture 33: IEEE standardization process (source: IEEE.org)

The completion of the first step means that a proposal has already been recognized as an emerging market need and it needs standardization. The next step (where Tactile Internet belongs) comprises the completion of a draft by working groups with the functional requirements and specifications. In the case of IEEE, a sponsor not only ensures the proper collaboration of group members but also draws the technical content and its nature. Through a series of meetings and workshops, experts write an official document that is published not only to the other members but also to the public to gather feedback and support. Subsequently, the standard gets approved by the board and testing and experiments are conducted to ensure the outcome quality (security, interoperability, reliability) in the technology sectors. Proper implementation means drawing the rules for future successful adoptions in the industry. After its final publishing, a continuous process on updating and reviewing the standard makes sure that it is in line with market needs.

7.2 Contributions

Worldwide implementation of Tactile Internet should be preceded by its international standardization in order to achieve the desired market consolidation. As Tactile Internet aims to a *niche* market, its standardization should comprise the collaboration of companies between the so-called alliance groups. They should agree on product specifications and expected market impact. By remaining close to the standardization process they should make sure that Tactile Internet services and products of their companies include the upcoming standards. It is a proven way to both shorten the time to market and to meet customer demands. Members of these groups develop and test new technology solutions for standards before the final approval from standards organization bodies.

Because Tactile Internet is a great innovation, it will not be easy for these organizations to follow the deep transformations in the new technology. This is because it will take some years to complete the standardization process to ensure that it will fit properly in the markets. There is always the case that companies develop technologies way before standards existence. For example researchers have not yet agreed on 5G network architecture (Tactile Internet will be supported by 5G) and the standardization process has just begun with global participation. However, companies are already claiming (not just to draw attention) about implementing experimental 5G solutions by 2018 looking forward to maximizing contributions to standardization process through already acquired patents.

3GPP

3GPP is a major player in 5G standardization roadmap. Related work that fits into Tactile Internet ecosystem includes:

TR22.862, a document that studies the requirements of critical communications in the context of 5G is part of the project SMARTER. More specifically it examines the adoption of low latency, reliability and high availability by the network operators.

TR 22.864 focuses on flexibility and adaptability on network functionality and services. More specifically, network slicing, efficient user plane, network capability exposure and multipoint connectivity.

TR 23.714 is a study by the Architecture Working Group that analyzes architectural designs for CN (Core Network) devices to support flexibility for network deployment and operation.

TR 32.842 is related to the management of virtualized networks with Virtual Network Functions considered in CN devices and Macro BS with the goal of determining interfaces and procedures.. It is a study by 3GPP Telecom Management Working Group.

TR 38.913, a document that contains scenarios and requirements for next generation access technologies, KPIs and on the requirements of deployment services. The objective is to analyze the physical and access network architecture related to carrier frequency, user density etc.

ETSI

As discussed in chapter 6.2, 5G networks are expected to be based on SDN functionality and NFV architecture. The separation of hardware and software introduces benefits which ETSI ISG is working over, such as the migration towards open infrastructure for NFV in 5G. Its aim is to provide the ground for open source initiatives that will drive standardization for virtualization of network functions, consolidation of network services and operation support systems. The implementation of this concept in the edge of cellular Core Network creates a possible infrastructure which could reserve resources in Radio Management systems aimed for Tactile Internet services.

The same vision is shared by the Next Generation Mobile Networks Alliance (NGMN). Its most important contribution for network operators in this field is the concept of network slicing. Different service requirements can be met by the same physical network architecture using the slicing approach both in CN and RAN domain. Real-time and high-reliable communications are among the highly desired services for businesses from next generation networks. Furthermore, the creation of the working group IPv6 -based Tactile

Details of 'DGS/IP6-0014' Work Item Schedule

Code	Status	Milestone	Action	Action Nb	Target	Achieved	Version
0	**Creation of WI by WG/TB**	Creation of WI by WG/TB			2015-05-29	2015-05-29	
0 p	**WI proposed to TB**	WI proposed to TB				2015-05-29	
0 a	**TB adoption of WI**	TB adoption of WI			2015-07-16	2015-06-23	
1	**Start of work**	Start of work			2015-06-23		
2	**Early draft**	Early draft			2015-10-01	2015-07-09	0.0.1
4	**Stable draft**	Stable draft			2016-03-28		
6	**Final draft for approval**	Final draft for approval					
8	**TB approval**	TB approval			2016-12-15		
8 A	**Draft receipt by ETSI Secretariat**	Draft receipt by ETSI Secretariat			2016-12-29		
12	**Publication**	Publication	PU		2017-01-26		1.1.1

Picture 34:IPv6 based Tactile Internet (source: ETSI)

Internet under the industry specification group IP6 (Picture 34) will publish its final draft by the end of January 2017. Its main contributions will focus on the following areas:

- Impact of Tactile Internet
- Mobile Edge Cloud- an agile approach
- Routing techniques that minimize latency
- Caching for neighbor discovery in IPv6
- Proximity through unicast addressing

ITU

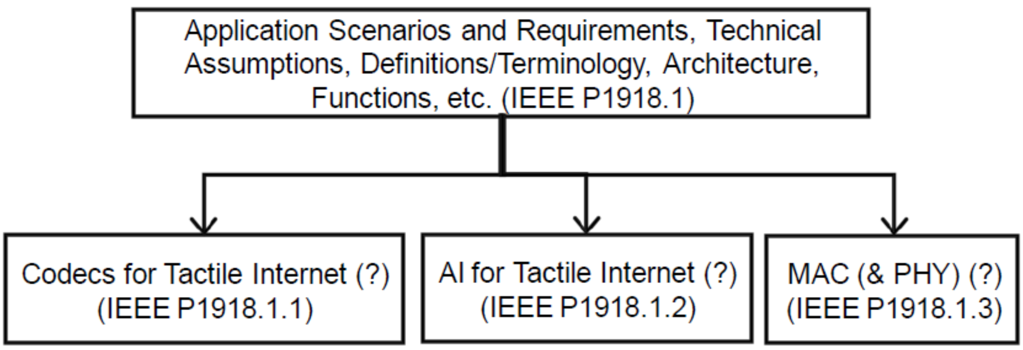
The International Telecommunications Union (ITU) has analyzed the Standards Gap through a report study (TD208) in four out of five areas which to my knowledge are relevant for Tactile Internet applications:

- High-level network architecture to support flexible virtual networks that support different service requirements such as throughput, latency ect. In this context the programmability of the network is introduced by separating control and data planes and should ensure end to end operations.
- End-to-end QoS framework that focuses on a different concept of collective performance on closed loop connectivity. Specifically redefining of QoS through new use cases and parameters variety should lead to additional standardization.
- Mobile front haul and back haul that focuses on solutions how to handle the transport bandwidth basically due to the enhancements in bandwidth, cell density and antenna arrays (MIMO)
- Network softwarization that describes the trend for designing, implementing, deploying and managing network equipment and network components by software programming. Benefits of programming include flexibility and the rapidity of design that allow the re-design of network and services architecture during the products lifecycle.

IEEE

The IEEE is particularly active on standardizing building blocks of 5G. Effort is put not only to enhance present wireless standards to meet the requirements of next generation networks (e.g. spectrum sharing) but also towards organizing activities for standardization of possible 5G technologies. New working groups are formed under the Standard Development Board that are important to Tactile Internet domain such as: P1914.1-Standard for Packet-based Fronthaul Transport Networks which enables the implementation of MIMO (Massive Input Massive Output), CoMP (Coordinated Multipoint Transmission), transmission and reception, therefore increasing network flexibility. P1915.1, P1916.1, P1917.1 are standards for Software Defined Networking Security, Performance and Reliability respectively.

A new standards working group (IEEE P1918.1) has been formed on the Tactile Internet, Application Scenarios, Definitions and Terminology, Architecture, Functions, and Technical Assumptions. It was approved after a proposal from the Technical University of Dresden on this issue. The first meeting was in May (Kuala Lumpur) 2016 under the IEEE International Conference on Communications. It drew attention from important industry players and contributions were given particularly on the technical definition, use cases, architecture and functionalities. Nokia and the Kings College of London were the leaders of the meeting with the latter adding important information. It stressed the importance of CoMP to meet the requirements of Tactile Internet such as latency and reliability. New ideas were proposed on the use of massive MIMO antennas on emerging millimeter wave (mm Wave) and the use of frequencies from 1 GHz to 100 GHz. Furthermore, due to contribution to codecs for Tactile Internet and Artificial Intelligence for Tactile Internet, 3 more working groups' standards (Picture 35) were formed under parent group IEEE P1918.1. The IEEE P1918.1.3 is not yet considered relevant to Tactile Internet by its committee but it may change status by next year.



Picture 35: Working groups on Tactile Internet Standards (source: IEEE)

Contributions from telecommunications players are expected to be adopted by the P1918.1 group with the view of publishing the standard by mid-2018.

7.3 Conclusions

The coexistence of human senses in the real and the virtual world opens up new possibilities towards societies' transformation. Tactile Internet will add a new dimension to the digital world with unprecedented human to robots interaction. Its requirements should be met by technologies being developed under the 5G umbrella. The biggest challenge remains the trade-off between metrics such as availability, security and bandwidth in order to guarantee ultra-low latency especially over wireless links. Future tactile Internet applications should run uninterruptedly over wireless links in order to cover a wide range of use cases for example smart traffic. The performance of 4G wireless network even in the ideal environment does not come close to meeting these requirements. Future research should focus on redesigning of networks that provide the functionalities on demand for tactile services. Making networks less complex, programmable and adding more control and capabilities to the radio access network, is key in this process. Nevertheless, applications may be able to run successfully over a few kilometres even with the existing technology provided that progress in computational power and tactile codecs is such that it does not impact to the latency budget. Therefore, experiments conducted indoors on Tactile applications conducted by public private partnerships will be critical in contributing towards standards development. As research continues in the 5G ecosystem, Tactile Internet will provide the ground for the emerging of fast, reliable and secure applications.

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