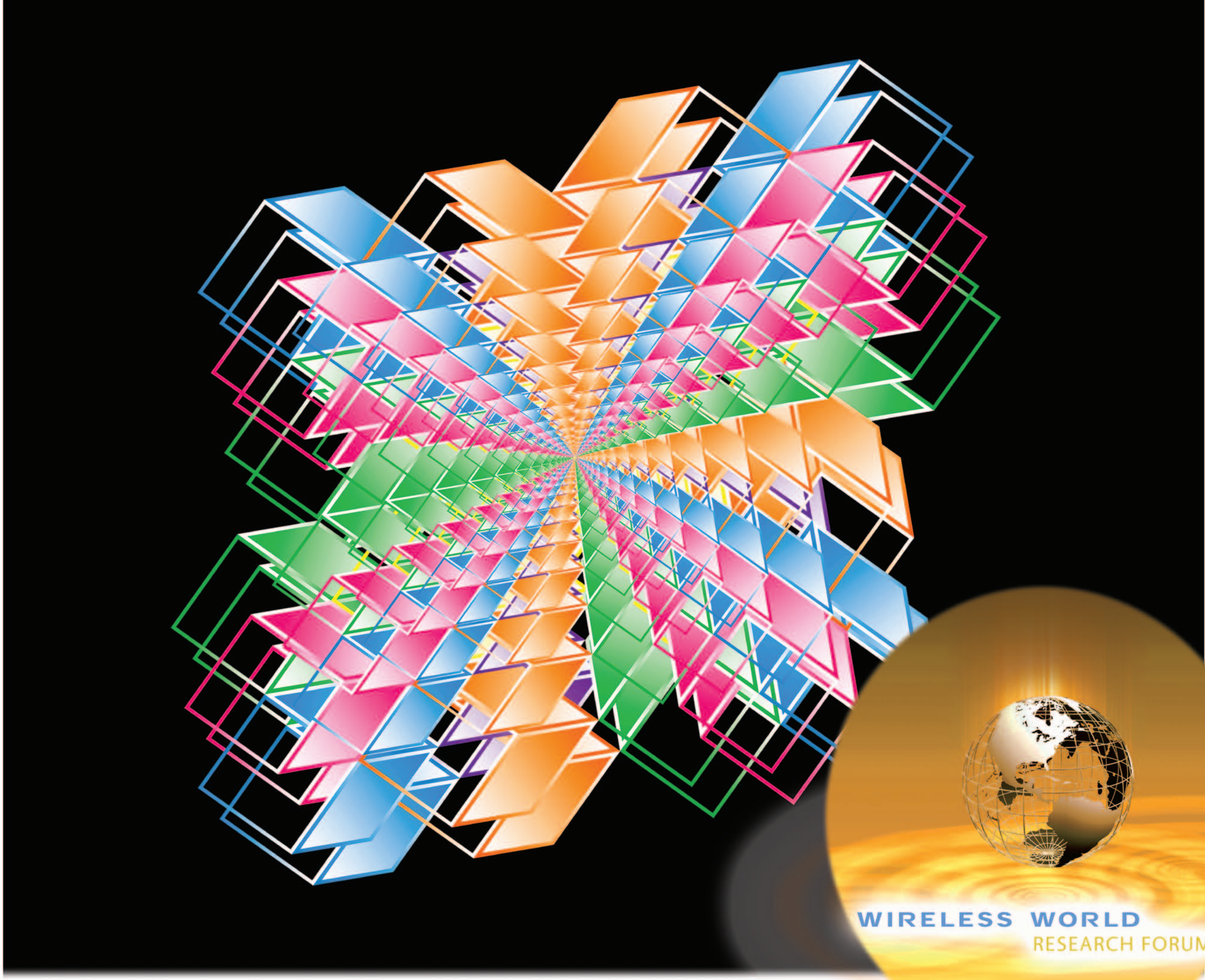

WIRELESS WORLD RESEARCH FORUM®

The Tactile Internet

Applications and Challenges

Gerhard P. Fettweis

Wireless communications today enables us to connect devices and people for an unprecedented exchange of multimedia and data content. The data rates of wireless communications continue to increase, mainly driven by innovation in electronics. Once the latency of communication systems becomes low enough to enable a round-trip delay from terminals through the network back to terminals of approximately 1 ms, an overlooked breakthrough—human tactile to visual feedback control—will change how humans communicate around the world. Using these controls, wireless communications can be the platform for enabling the control and direction of real and virtual objects in many situations of our life. Almost no area of the economy will be left untouched, as this new technology will change health care, mobility, education, manufacturing, smart grids, and much more. The Tactile Internet will become a driver for economic growth and innovation and will help bring a new level of sophistication to societies.

Changing Technology for a Changing World

Cellular communications have already been shaping the planet in an unprecedented way. Since the vast majority

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of people around the globe are connected by cellular communications, a logical next step is to connect the machines and devices as well. The success of cellular communications has flattened the planet and enabled countries with smaller economies to participate in the larger global economy. As a result, smaller countries now have the opportunity to become major players in worldwide trade and business. Also, cellular communications continues to play an important factor in growing economies, especially in the developing world [1].

So far, we have seen that cellular communication enables content to be moved around the globe, where prominent examples of content are voice telephony, text messaging, video streaming, e-mails, and file sharing. The exponentially growing advances in electronics have led to an exponential increase in the volume and size of the content to be transmitted. This again has resulted in the need to develop cellular standards that can handle increasing data rates. Hence, to understand the future potential growth of wireless data rates, the future advances in electronics must be analyzed and understood.

However, there is another frontier to be considered in conjunction with the race for improved data capacity. When comparing the advances in the orders of magnitude of increase in data rate with the reduction in round-trip latency of interaction, the latter has not dropped below the requirement for telephony. Long-term evolution (LTE) achieves a typical round-trip latency of 25 ms [2], exceeding the 10-ms requirement needed to enable real-time wireless gaming.

When moving to a round-trip latency of 1 ms, along with carrier grade robustness and availability, a new breakthrough enabling unprecedented mobile applications becomes viable. These applications are called the *Tactile Internet*, as this is the typical interaction latency required for tactile steering and control of real and virtual objects without creating cybersickness. This will revolutionize education, mobility and traffic, health care, sports, entertainment, gaming, and the smart grid, just to name some segments, which can already be seen. The Tactile Internet will dramatically reshape our society.

A Sneak Preview on Future Electronics

Flash memory is the key storage technology for mobile devices today. Flash storage capacity is currently doubling every 18 months, which equals an increase by one order of magnitude (ten times) every five years [4]. With the introduction of parallel machines, microprocessor processing capability has continued to experience the same exponential increase. Hence, as processing and memory capacity continue to scale, so does the need to move results/files, and therefore, the crest for communications bandwidth is unrestrained.

The semiconductor technology scaling is slowing down; however, three-dimensional (3-D) integration is becoming available. In the past, we designed silicon chips, wire, and flip-chip bonded in a package. With the current advent of 3-D chip integration, as, e.g., championed by Samsung [5] for memories so far, further advances will allow companies to develop 3-D chip-stacks for complex systems. This means that the integration from a package to complex systems is bounded not by technology scaling but by the prospects of stacking many chips within a 3-D chip-stack [6]. Therefore, the end of integration is not in sight, and the requirement for communications bandwidth is not either.

THE EXPONENTIALLY GROWING ADVANCES IN ELECTRONICS HAVE LED TO AN EXPONENTIAL INCREASE IN THE VOLUME AND SIZE OF THE CONTENT TO BE TRANSMITTED.

However, one aspect is limiting this technology roadmap: the I/O bandwidth of devices. Chips or 3-D chip-stacks need to be connected on a board, and boards must be connected to a backplane within a chassis. To address the interconnect challenges, solutions are being researched. Optical waveguides embedded in boards and optical integrated transceivers within chip-stacks can possibly enable breakthroughs in communications bandwidth. Furthermore, copper backplanes could be replaced by fully wireless chip-to-chip interconnectivity of boards in a chassis, again enabling increased bandwidth by more than three orders of magnitude beyond what we see today. This is the communications concept behind building the highly adaptive energy efficient computing (HAEC) box or system [7].

When combining 3-D integration and possible advances in interconnection as previously detailed, it could be feasible to build an exa-scale computing system with at least 1 billion computing nodes within a cube with a volume of on liter ($10 \times 10 \times 10$ cm^3). In Figure 1 and [7]; we refer to this as a *HAEC box vision*. A consequence of this vision is that an exa-scale amount of compute power could be placed in every access point or base station of future wireless systems. Hence, a future mobile edge cloud system of unprecedented local computing power could be created, enabling many new applications and services that cannot be foreseen at this point in time.

Wireless Roadmap—The Race for Data Rates

Cellular technology dominates today's life, and the appetite for bandwidth seems to be without foreseeable limits. We can observe a steady increase in data rates provided by wireless technologies by approximately ten times every five years, which is equivalent to Moore's law of doubling every 18 months. A key driver in need for higher data capacities is most likely the continuous increase in storage and computing within mobile devices. Furthermore, with the vision of a HAEC box possibly becoming a reality, advances in electronics are expected to continue

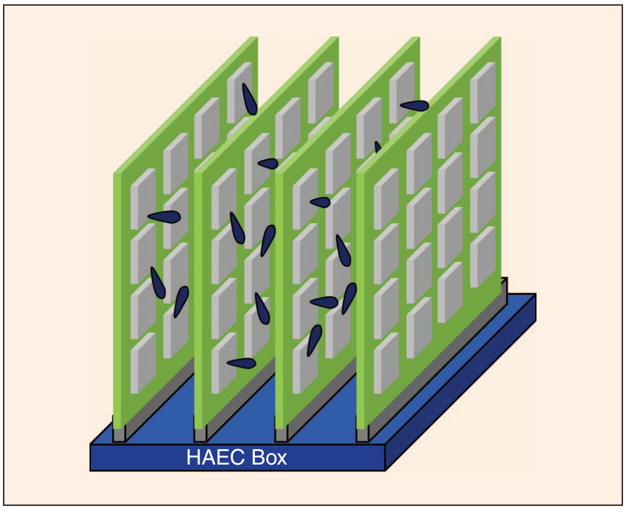

FIGURE 1 The vision of a HAEC box, including embedded on-board optical interconnects and a wireless backplane of chip-stacks interconnecting with other chip-stacks on neighboring boards via a wireless (beam-steered) connection [7]. By having four boards, as depicted, with 16 chip-stacks within 10 × 10 × 10 cm^3, and every stack comprised of 128 chips with 128,000 cores each, 1 billion processing nodes could be packaged in an HAEC box.

A CONSEQUENCE OF THIS VISION IS THAT AN EXA-SCALE AMOUNT OF COMPUTE POWER COULD BE PLACED IN EVERY ACCESS POINT OR BASE STATION OF FUTURE WIRELESS SYSTEMS.

for more than the next two decades at a typical rate of Moore's law. Hence, the appetite for more data over wireless communications will continue to increase as well.

The introduction of each previous digital standard of the Third Generation Partnership Program (3GPP) family has taken place approximately once a decade driving the unrestrained race for data along this exponential increase.

Today, it is widely accepted that LTE is the new generation of cellular communications; therefore, it is denoted as the *fourth generation (4G)*. In the next step, referred to as LTE-Advanced, data rates of more than 100 Mb/s will be achievable. When projecting future needs for data, a fifth-generation cellular system will likely be available in 2020–2030, and cellular data rates of 1–10 Gb/s must become reality (see Figure 2). Wireless local area network (WLAN) technology has been driving along the same increase over the years, with a steady ten times improvement every five years. This requires a 100-times higher data rate projection than cellular.

Clearly, we have seen an unprecedented line of applications becoming possible because of the available bandwidth. For example, mobile Internet via smartphones, social networks, and search engines were unforeseeable 20 years ago. However, data alone is not the only driver of innovation. When considering the impact the iPhone had on the cellular market, we see that it was not a leader in high bandwidth of connectivity but was introduced with a cellular modem lagging a generation behind. The iPhone, however, had an unprecedented haptic interface, enabled by gyroscopes and a new quality level of touch screen technology. Therefore, it is likely that there is another major step ahead that could heavily change the way we interact. Within this article, the proposal is made that the Tactile Internet could fulfill that role.

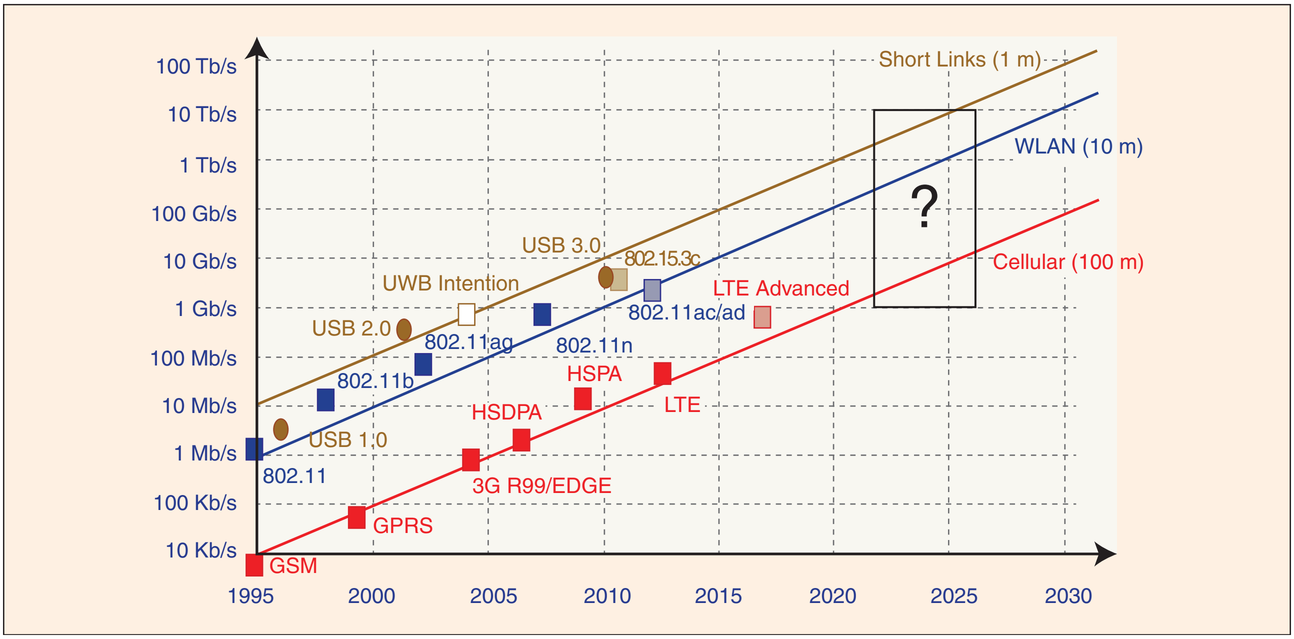

FIGURE 2 The wireless roadmap of standards and their achievable data rates at time of their market introduction; also see [8].

The Tactile Internet—Real-Time Context

Real-time interaction with our environment is crucial to human beings. As humans, we have many ways of defining real time since driving cars and making phone calls and the tactile sensation of touching surfaces actuate many different sensors and real-time interaction controls in our body system. To simplify, a brief review of a coarse granularity of different levels of real time shall be discussed here. We define an interaction (service) to be real time when the communication response time is faster than the time constants of the application; hence, making the delay incurred by communication and computing negligible within the context is considered. Here, we discuss only four types of physiological real-time constants, with further details given in [3] and [11]: muscular, audio, visual, and tactile. For literature on human reaction analysis, refer to [9], and the overview is given in [10].

How fast is fast? This question of speed must be answered within the context of a desired service and/or application (see Figure 3). In the case of muscular reaction times, e.g., reacting to a fly settling on one of our limbs, the typical time is about a second. When listening to voices and reacting within a conversation, latency of up to 100 ms is nonobservable. When watching a movie, a frame rate of 100 Hz is acceptable, which relates to a latency of 10 ms between frames.

However, when tactile steering and/or control of an object is carried out while simultaneously seeing or hearing its reaction, a reaction latency of 10 ms or less needs to be achieved. An example of this is moving an object on a touch screen. Since the typical speed of our finger moving on a touch screen is 1 m/s, the reaction time of the screen must be 1 ms to achieve an unnoticeable displacement of 1 mm between the finger and the object to be moved. Assuming a latency of 100 ms was implemented, this would lead to an unacceptable displacement of 100 mm, i.e., 4 in. Even 10-ms latency, which leads to 10-mm displacement, is clearly noticeable.

Similar studies on short latency requirements are done by professional audio systems providers. Because a latency of less than 5 ms is difficult to achieve with digital communications, a majority of professional audio systems (e.g., wireless stage microphones and mixing desks) are in analog. Another area in which this short latency constraint has been noticed is virtual reality and augmented reality. Synchronization between the ear and the eye has to be below 10 ms to prevent simulator sickness, which is now typically referred to as cybersickness [12].

In case the feedback is given physically by a haptic system, it is referred to as haptic communications [13]. Here, we refer to the Tactile Internet as a system which has tactile input and also audio and/or visual feedback, requiring extremely short latency.

EXOSKELETONS ARE DEVICES THAT ARE STRAPPED TO THE BODY AND LIMBS, ENABLING ONE TO MOVE HIS/HER LIMBS WITH MORE FORCE THAN HIS/HER MUSCLES.

The Tactile Internet—Application Scenarios

The scenarios above show why a short 1-ms reaction time is the new level of system performance. It is clear that a round-trip latency is discussed, i.e., a tactile sensor reads information and a connected system reacts with actuators seen by the same human within 1 ms.

As current WLAN and cellular systems do not yield anything close to achieving a round-trip latency of 1 ms, it is difficult to comprehend all the new applications that can emerge. Next, some examples are provided to show the ground-breaking potential of the new Tactile Internet.

Health Care

The University of California Berkeley's Robotics and Human Engineering Laboratory has shown that people who were confined to using a wheelchair were able to walk with exoskeletons. This has drawn a lot of attention worldwide, also showing promising results giving patients with cross-section palsy the ability able to walk again [14]. Exoskeletons are devices that are strapped to the body and limbs, enabling one to move his/her limbs with more force than his/her muscles. The reaction time of an exoskeleton has to be fast enough that movements are within tactile latency. We can envision that no elderly person will have to use a walker but instead can simply strap on an exoskeleton. These must be controlled by wireless systems recognizing other people with/without exoskeletons as well as the individual's surroundings. In both cases, this is so that the individual does not harm others or the surroundings, e.g., not falling down stairs or running into objects with the force of an exoskeleton. However, if we can build wireless systems with tactile latency, a whole new world can open up for physically impaired people. Independent of one's current physical ability, many people will be able to freely move around again.

Many applications in the manufacturing and construction industry also can be foreseen by the use of exoskeletons. Again, in many cases, a low tactile latency

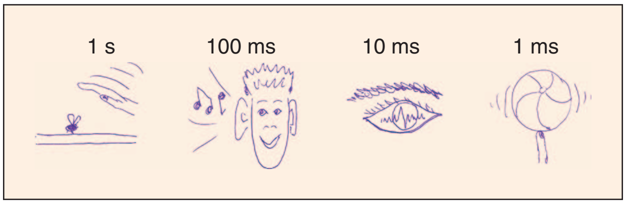

FIGURE 3 A coarse grain analysis of human reaction and interaction times [3].

PLATOONING OF VEHICLES IS THE JOINT FORMATION OF A LINE OF CARS TRAVELING AT THE SAME SPEED WITH A VERY SHORT DISTANCE FROM EACH OTHER.

(below 10 ms) with other objects must be enabled to make the application safe.

Education and Sports

The concept of using exoskeletons connected wirelessly can also be used for training physical movements for sports (such as surfing), maneuvering vehicles, or operating machines in virtual training centers before going live. In addition, this can be used for remote physiotherapy, i.e., strapping on exoskeletons and being connected to a therapist, thus executing training sessions without having to physically visit the therapist's office.

The possible variety of applications is vast for this educational concept enabled by the Tactile Internet. It will provide endless possibilities for the improvement of education. An example of one potential new possibility is an interactive virtual history session, where a classroom jointly engages, via a virtual reality setting, in experiencing the old Rome.

Traffic

The Tactile Internet with approximately a 1-ms round-trip delay could revolutionize mobility. Assume that in cities all vehicles were driving at 10 m/s (36 km/h or 20 mi/h); a car could then come to a full stop within 10 m, i.e., 2 s. Fully automatic driving would be possible, making traffic lights superfluous as vehicles could zip through intersections without crashing. Also, a pedestrian could engage a personal bubble with his/her cell phone, which makes sure that no car hits the person when crossing roads.

Platooning of vehicles is the joint formation of a line of cars traveling at the same speed with a very short distance from each other. Its introduction could generate better fuel efficiency, but this requires tight stability control of the platoon of cars. Today, the electronic stability control (ESC), also referred to as *electronic stability program (ESP),* of a vehicle must be synchronized between wheels within 1–2 ms to ensure that the car does not lose stability. However, in the case of a platoon of cars with ESC/ESP, the complete platoon needs to have coordinated actions among wheels. Hence, all vehicles of a platoon need to be connected with 1–2 ms latency.

Another application could be remote driving. If the weather makes the driver feel unsafe, a call center will be available for taking over control of the car and remotely driving it to the desired destination. However, tactile control must be possible to ensure real-time feedback for safe remote driving.

Robotics and Manufacturing

Controlling robots must happen at latency reaction times that are fast enough for the robot and its object not to start mechanically resonating. For many robotics scenarios in manufacturing, this has led to a maximum latency target of a communication link of 100 μs and a round-trip reaction time of 1 ms, the same target discussed for the Tactile Internet.

Henry Ford introduced the assembly line for mass production of one model. Today, a diversified product portfolio should be produced within one assembly environment. This, however, can make robots remain idle at times when a product being assembled does not require its engagement. Hence, a future factory could have mobile robots join assembly lines or assembly points just in time for their action. In this case, a wireless infrastructure of the Tactile Internet will be necessary. (For industrial manufacturing communications requirements, see http://www.bmbf.de/foerderungen/22967.php.)

Free-Viewpoint Video

Digital image processing of video information can be used to synthetically render the viewpoint of the viewer to another spot, named free-viewpoint video [15]. In the future, the choice of point of view can be dynamically modified, allowing the projection of an extended view beyond one's current viewpoint. An example of interest could be viewing a sports event in a stadium equipped with hundreds of cameras. Real-time rendering of these cameras allows each person to choose their viewpoint of interest, e.g., the viewpoint of the favorite player on the field. This is projected onto the personal tablet or smartphone carried by the stadium visitor. To maximize excitement, the latency between the naturally visible surroundings by a visitor and the free viewpoint video being displayed on the tablet must be minimized. Again, a 1-ms latency would generate a fully synchronized experience without creating cybersickness.

Video cameras in cars and smartphones could be connected and rendered into a free viewpoint video, not only in stadiums but also between cars on the road, between vehicles in logistics hubs, and between pedestrians in crowded areas. This would always allow one to project his/her own viewpoint into a free viewpoint of choice at tactile latency.

Smart Grid

Another application area is the synchronization of suppliers in a smart grid. As synchronous cophasing of suppliers is necessary to minimize reactive power, this must be achieved within a small angle of phase. A 1-ms latency of communications between (local) suppliers can ensure an 18° (50-Hz ac network) or 21.6° (60 Hz) phase coherence.

The Paradigm Shift

The Tactile Internet is a big paradigm shift ahead. It enables us to engage with objects in our environment at tactile latencies. Today, communications technology is widely used for moving content from A to B. Content can be multimedia or static, e.g., video streams, data files, voice class, or e-mail. By making the Tactile Internet happen, we can engage and steer real and virtual objects directly at tactile real-time interaction speeds. Hence, the primary goal of communication is to provide the necessary infrastructure for this technology. Not only does content need to be transported, but control information must now be transported as well. The paradigm shift of the Tactile Internet is that communications are built for enabling steering and control, a big shift from moving only content.

Figure 4 depicts this paradigm shift from content to controls. This opens up completely new opportunities for existing and new applications in many fields, of which Figure 4 only lists a few.

Some Key Challenges Ahead

Obviously, requiring a 1-ms round-trip latency is a huge challenge. The physical transmission must have very small packets to enable a one-way physical layer transmission of 100 µs. To achieve this, each packet cannot exceed a 33-µs packet duration. The reason for this is the structural additional latency, which needs to be introduced by encoding the packet at the transmitter, and its detection and decoding at the receiver. This limits the packet size to less than one-third of the target latency. This clearly indicates that the modulation used in current LTE cellular systems is not a viable proposal, as the duration of one orthogonal frequency division multiplexing (OFDM) symbol alone is close to 70-µs long. A complete rehaul of the cellular physical layer is necessary for the Tactile Internet, which might become reality with the fifth-generation system.

Current systems also have little provisioning for defining the minimum latency of protocol handling. A Transmission Control Protocol (TCP)/Internet Protocol packet arriving at a base station, which is labeled requiring a tactile latency, must be routed directly to the physical layer for transmission. Today, the latency of wireless communications is mainly analyzed by evaluating the structure of the medium access control (MAC) as well as by the latency required for the signal processing of the physical layer. However, protocol processing will become a major challenge for making the Tactile Internet possible. Steering and control packets arriving at a base station must be handled immediately and tunneled into a reserved MAC slot. It certainly looks more like a circuit-switching challenge in terms of latency and packet reservation guarantees than today's mainstream packet switching paradigm.

THE PARADIGM SHIFT OF THE TACTILE INTERNET IS THAT COMMUNICATIONS ARE BUILT FOR ENABLING STEERING AND CONTROL, A BIG SHIFT FROM MOVING ONLY CONTENT.

Another key challenge is to be able to provide carrier grade access reliability and robustness. Fixed-line carrier grade requires, e.g., an uptime of the system of so-called seven nines (99.99999%), i.e., a failure rate of 10^{-7}. If we move to having objects of our environment being steered and controlled by the Tactile Internet, reliability of a link as well as availability of setting-up connectivity are of utmost importance. A failure rate below 10^{-7} might even be necessary in some cases. This translates into an annual outage of only 3.17 s. How can this be achievable? Today, wireless systems are built under the impression that a link with 3% outage is a good link. This is far from 10^{-7}. However, when two links with uncorrelated channels are combined, 3% outage per link generates a combined outage of approximately 10^{-3}. Five uncorrelated links can achieve a carrier grade outage of less than 10^{-7}.

Today, a hot topic of cellular systems is carrier aggregation. In the case of interband carrier aggregation, it can be assumed that the links have uncorrelated channels. Another current issue in the design of cellular systems is coordinated multipoint [16], or interference cancellation and interference coordination. In the special case of achieving this by distributed multiple-input, multiple-output (MIMO), the mobile phone must be connected to at least two base stations simultaneously. Again, this creates parallel uncorrelated links, which are used for increasing the data rate and fairness. However, these uncorrelated links can also be aggregated to reduce the outage instead. Hence, building wireless connectivity that achieves carrier grade outage is not an insurmountable problem, but can

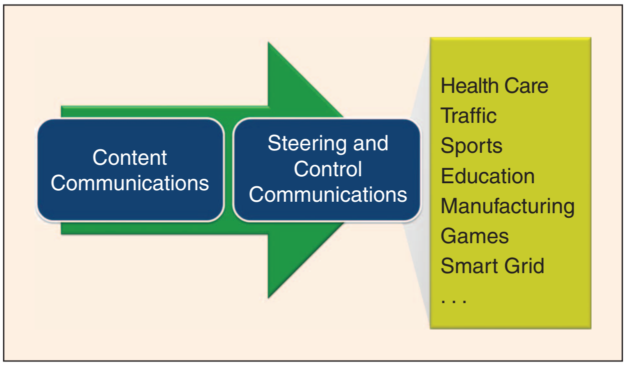

FIGURE 4 The road ahead enabled by the Tactile Internet—stepping from moving content to controlling and steering real and virtual objects of our environment. This enables applications in many segments, a few of which are listed.

be fixed by using access diversity by connecting to multiple base stations or via multiple carriers simultaneously.

To achieve a round-trip latency of 1 ms, the communication delay due to the speed of light needs to be considered as well. Within 1 ms light travels 300 km, i.e., the maximum distance for a steering and control server to be placed from the point of tactile interaction by the users is 150 km away. However, this assumes no processing delays in the communication. Taking the additional signal processing, protocol handling, and switching delays into account, this requires the control/steering server to be in the range of 15 km from the tactile point of interaction.

Extremely powerful servers, such as the HAEC box, have to be built as close to the base station as possible, i.e., at the edge of the mobile radio access network. This is called *the mobile edge cloud concept*. The best solution is to combine servers into the same box as base stations and access points. In addition, the HAEC box, like servers, must have real-time operating systems, which can guarantee a short response time.

Users can be mobile, requiring a handoff of the communication link(s) from one base station to another. However, an application connected to the user will be running on a local HAEC box like server. Hence, in addition to the communications handoff, the hardware and software system running on these servers must also be built for the handoff of a running application from one server at one base station location to the next one.

Finally, another challenge is providing safety and security of the Tactile Internet and its applications. Clearly, if we rely on the Tactile Internet to provide daily applications, it can cause harm if it does not operate properly. Data integrity and accountability must be provided as well.

Conclusions

Today's wireless communication is designed for transporting content. The breakthrough lying before us is to enable wireless steering of our environment by enabling the Tactile Internet [17]. Some features must be achieved before this technology can be utilized; most importantly, a short round-trip latency of approximately 1 ms is necessary. In addition, a 99.99999% carrier grade robustness and availability must be developed and provided. Once these challenges have been addressed and solutions have been found, the Tactile Internet will enable an unforeseeable plurality of new applications, products, and services. Discovering the world of the Tactile Internet will become a main driver for innovation the world's economies. Societies will change with many new services becoming available; this, in turn, will help make the planet a better place to live.

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