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The Tactile Internet: Vision, Recent Progress, and Open Challenges

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To facilitate a better understanding of the Tactile Internet, the authors first elaborate on the commonalities and subtle differences between the Tactile Internet and the Internet of Things and 5G vision. After briefly reviewing its anticipated impact on society and infrastructure requirements, we then provide an up-to-date survey on recent progress and enabling technologies proposed for the Tactile Internet.

ABSTRACT

The advent of commercially available remote-presence robots may be the precursor of an age of technological convergence, where important tasks of our everyday life will be increasingly done by robots. A very low round-trip latency in conjunction with ultra-high reliability and essentially guaranteed availability for control communications has the potential to move today's mobile broadband experience into the new world of the *Tactile Internet* for a race with (rather than against) machines. To facilitate a better understanding of the Tactile Internet, this article first elaborates on the commonalities and subtle differences between the Tactile Internet and the Internet of Things and 5G vision. After briefly reviewing its anticipated impact on society and infrastructure requirements, we then provide an up-to-date survey of recent progress and enabling technologies proposed for the Tactile Internet. Given that scaling up research in the area of future wired and wireless access networks will be essential for the Tactile Internet, we pay particular attention to the latency and reliability performance gains of fiber-wireless (FiWi) enhanced LTE-Advanced heterogeneous networks and their role for emerging cloudlets, mobile-edge computing, and cloud robotics. Finally, we conclude by outlining remaining open challenges for the Tactile Internet.

INTRODUCTION

The IEEE Digital Senses Initiative (DSI) is the newest initiative by the Technical Activities Board Future Directions Committee, launched in June 2015. DSI is dedicated to advancing technologies that capture and reproduce various stimuli (e.g. sight, hearing, touch, smell, and taste) from the outside world and let humans as well as machines perceive and react to the combined stimuli in various ways. An interesting early example is the commercially available oPhone, which allows smartphone users to send digital scent messages with more than 300,000 unique aroma combinations.[1] Another example is remote-presence robots, e.g. Suitable Technologies' *BeamPro*, which consist of a flat screen and video camera mounted on a mobile pedestal.

In an interview in 2013, we reflected on a future economic "golden age" of technological convergence in the 2020s, where important tasks of everyday life may be increasingly done by robots [1]. As a personal example, we envisioned the desirable possibility of not only monitoring but also acting from Canada remotely via the Internet in support of our elderly parents living in Germany. This vision of the Internet is now widely known as the so-called *Tactile Internet*, a term first coined by G. P. Fettweis in early 2014 [2, 3]. The Tactile Internet is expected to have the potential to create a plethora of new opportunities and applications that reshape our life and economy. A preliminary market analysis has revealed that the potential market could extend to US$20 trillion worldwide, which is around 20 percent of today's worldwide GDP [4].

In various real-time cyber-physical systems (CPSs), including virtual and augmented reality, an extremely low round-trip latency of below 1 ms is required. An important CPS example is the smart grid and its fast response time requirements in the event of (cascading) power network failures. Current cellular and WLAN systems miss this target by at least one order of magnitude. A round-trip latency of 1 ms can potentially move today's mobile broadband experience into the new world of the Tactile Internet. Beside voice and data communications, current 4G mobile networks enable real-time access to richer content and enable early applications of machine-to-machine (M2M) or machine type communication (MTC). Once machines become connected, the next natural leap is to have them controlled remotely. This will generate a completely new paradigm for control communications to steer/control elements of our surroundings and environment [2]. A round-trip latency of 1 ms in conjunction with carrier-grade robustness and availability will enable the Tactile Internet for steering and control of real and virtual objects [3]. However, the Tactile Internet comes with a caveat: it should amplify the differences between machines and humans. By building on the areas where machines are strong and humans are weak, the machines are more likely to complement humans rather than substitute for them. The value of human inputs will grow, not shrink, as the power of machines increases [5].

To facilitate a better understanding of the

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[1] Visit http://www.oNotes.com for further information.

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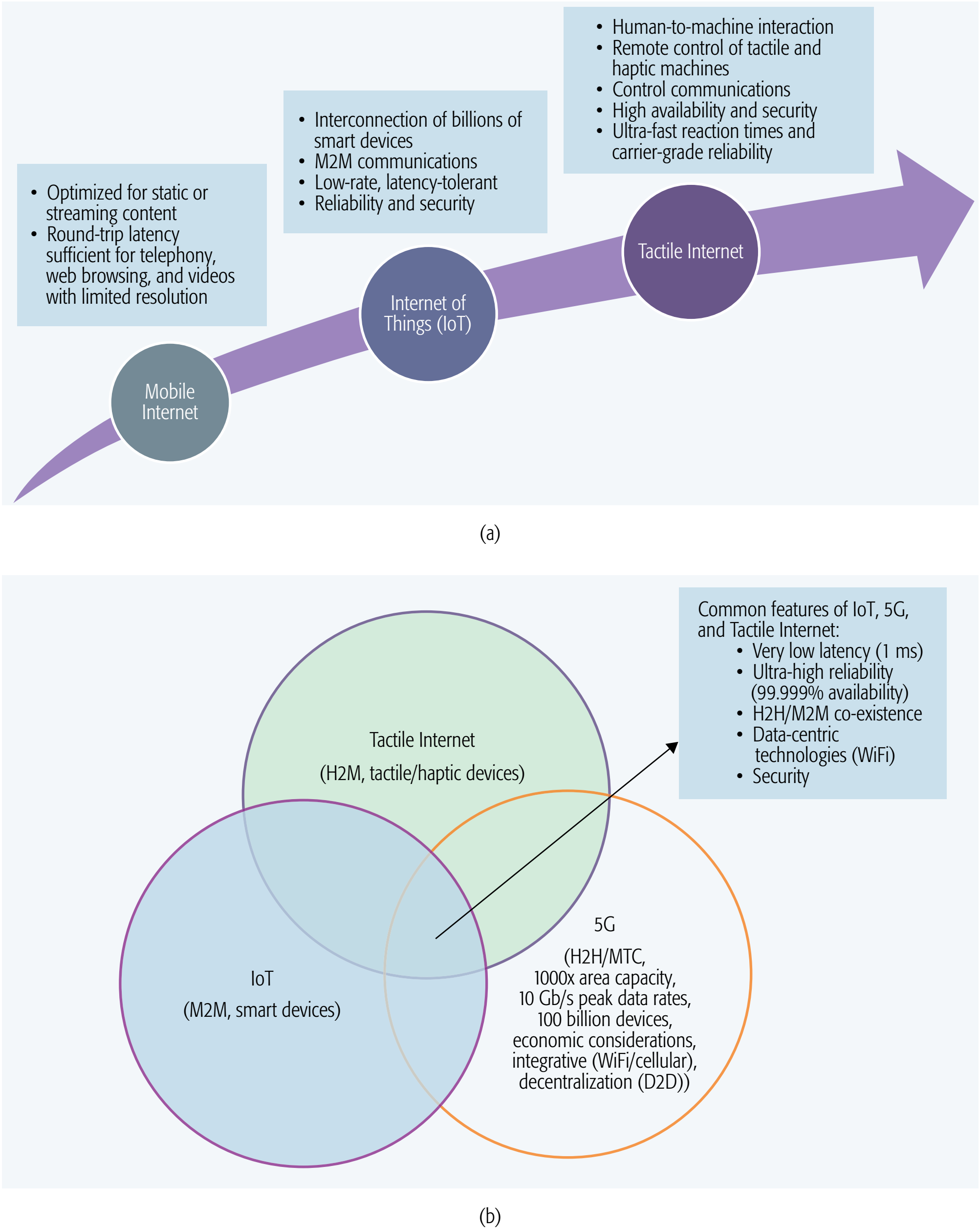


Figure 1. The Tactile Internet: a) revolutionary leap of the Tactile Internet (in compliance with ITU-T Technology Watch Report [7]); b) the three lenses of IoT, 5G, and the Tactile Internet: Commonalities and differences.

The Tactile Internet comes with a caveat: It should amplify the differences between machines and humans. By building on the areas where machines are strong and humans are weak, the machines are more likely to complement humans rather than substitute for them. The value of the human inputs will grow, not shrink, as the power of machines increases.

Tactile Internet, it is helpful to compare it to the emerging Internet of Things (IoT) and 5G mobile networks and elaborate on their commonalities and subtle differences. To begin with, it is worthwhile to mention that the concept of IoT is far from novel. In fact, the term "Internet of Things" was coined by Kevin Ashton from MIT no less than 20 years ago in 1995. However, it is only recently that we are witnessing the explosive growth of the IoT [6]. Figure 1a shows the revolutionary leap of the Tactile Internet according to a recent ITU-T Technology Watch Report [7]. The high availability and security, ultra-fast reaction times, and carrier-grade reliability of the Tactile Internet will add a new dimension to human-to-machine interaction by enabling tactile and haptic sensations. On the other hand, future 5G networks will have to be able to cope with the unprecedented growth of mobile data traffic as well as the huge volumes of data from the smart devices that will power the IoT. Toward this end, the 5G technology vision foresees 1000-fold gains in area capacity, 10 Gb/s peak data rates, and connections for at least 100 billion devices. The key challenge of 5G wireless access and core network architectures is to make it possible to address novel machine-centric use cases that are currently not addressed by cellular networks. Potential 5G applications range from industry, robots and drones, and virtual and augmented reality, to healthcare, road traffic, and smart grid [8]. Some of these envisioned 5G applications require very low latency on the order of 1 ms or less and ultra-high reliability

According to the ITU-T Technology Watch Report on the Tactile Internet, scaling up research in this area will be essential, ushering in new ideas and concepts to boost access networks' inherent redundancy and diversity to address the stringent latency and reliability requirements of Tactile Internet applications.

with essentially guaranteed availability. Thus, beside very low latency, 5G should enable connectivity, whose reliability will have to be orders of magnitude higher than in current radio access networks. Unlike the previous four generations, 5G will also be highly integrative. The integrative vision of 5G will lead to an increasing integration of cellular and WiFi technologies and standards. Another important aspect of the 5G vision is decentralization by evolving the cell-centric architecture into a device-centric one and exploiting intelligence at the device side (human or machine), for example via device-to-device (D2D) communication or user equipment (UE) assisted mobility.

Clearly, the discussion above shows that there is a significant overlap among IoT, 5G, and the Tactile Internet, though each one of them exhibits its unique characteristics. For illustration, Fig. 1b provides a view of the aforementioned commonalities and differences through the three lenses of IoT, 5G, and the Tactile Internet. The major differences may be best expressed in terms of underlying communications paradigms and enabling devices. IoT relies on M2M communications with a focus on smart devices (e.g. sensors and actuators). In co-existence with emerging MTC, 5G will maintain its traditional human-to-human (H2H) communications paradigm for conventional triple-play services (voice, video, data) with a growing focus on the integration with other wireless technologies (most notably WiFi) and decentralization. Conversely, the Tactile Internet will be centered around human-to-machine (H2M) communications leveraging tactile/haptic devices. More importantly, despite their differences, IoT, 5G, and the Tactile Internet seem to converge toward a common set of important design goals:

- Very low latency on the order of 1 ms.
- Ultra-high reliability with an almost guaranteed availability of 99.999 percent.
- H2H/M2M coexistence.
- Integration of data-centric technologies with a particular focus on WiFi.
- Security.

We note that there already exist recent excellent surveys on the Tactile Internet, most notably the aforementioned [3] and [8], which elaborate on its rationale and potential. However, both of these surveys take a rather 5G-centric approach with a focus on the wireless front-end and do not report on any early results and obtained findings. Conversely, this survey tries to approach the Tactile Internet from various angles and differs from previous Tactile Internet surveys in a number of ways. Specifically, our survey touches on the importance of high-speed fault-tolerant fiber backhaul infrastructures, as well as complementary technologies and techniques such as WiFi offloading and cloudlets, given that state-of-the-art robots, for example, Aldebaran's humanoid robot NAO, rely on WiFi and next-generation robots such as Softbank's Pepper, announced to become available for order in North America starting 2016, will be based on advanced cloud technologies. In addition, we provide a comprehensive up-to-date survey of results on lowering the delay and increasing the reliability performance of integrated fiber-wireless communications and control infrastructures based on data-centric Ethernet technologies in support of future Tactile Internet applications, including new results on emerging mobile-edge computing (MEC). The reported results are instrumental in providing insights into possible realizations of the Tactile Internet vision.

The remainder of the article is structured as follows. The following section further elaborates on the Tactile Internet vision by briefly reviewing its anticipated impact on society and important design guidelines. Then we provide an up-to-date survey of recent progress and enabling technologies proposed for the Tactile Internet. Following that we identify several open challenges and outline future research directions. Finally, we conclude the article.

TACTILE INTERNET: VISION AND DESIGN GUIDELINES

The vision of the Tactile Internet and its potential impact on society is expected to add a new dimension to human-to-machine interaction in a variety of different application fields, including healthcare, education, and smart grid. For a detailed description the interested reader is referred to [7]. The information and communications infrastructure enabling the envisioned Tactile Internet has to meet a number of design requirements. First and foremost, it has to provide a very low end-to-end *latency* of 1 ms and the highest possible *reliability* for real-time response. It also has to ensure both data *security* and the availability and dependability of systems, without violating the very low latency requirement due to additional encryption delays. These key design objectives of the Tactile Internet can only be accomplished by keeping tactile applications local, close to the users, which calls for a distributed (i.e., *decentralized*) service platform architecture based on cloudlets and mobile-edge computing (to be discussed in more detail shortly). Furthermore, *scalable* procedures at all protocol layers are needed to reduce the end-to-end latency from sensors to actuators. Importantly, the Tactile Internet will set demanding requirements for future *access networks* in terms of latency, reliability, and also capacity (e.g. high data rates for video sensors). Wired access networks are partly meeting these requirements already, but wireless access networks are not yet designed to match these needs. According to the ITU-T Technology Watch Report on the Tactile Internet [7], scaling up research in this area will be essential, ushering in new ideas and concepts to boost access networks' inherent redundancy and diversity to address the stringent latency and reliability requirements of Tactile Internet applications.

TACTILE INTERNET: RECENT PROGRESS

We have seen in the previous section that the Tactile Internet will set demanding requirements in particular for the design of future wired and wireless access networks. In [9] we recently introduced our concept of fiber-wireless (FiWi) enhanced LTE-Advanced (LTE-A) heterogeneous networks (HetNets), where the traditional barriers between coverage-centric 4G mobile

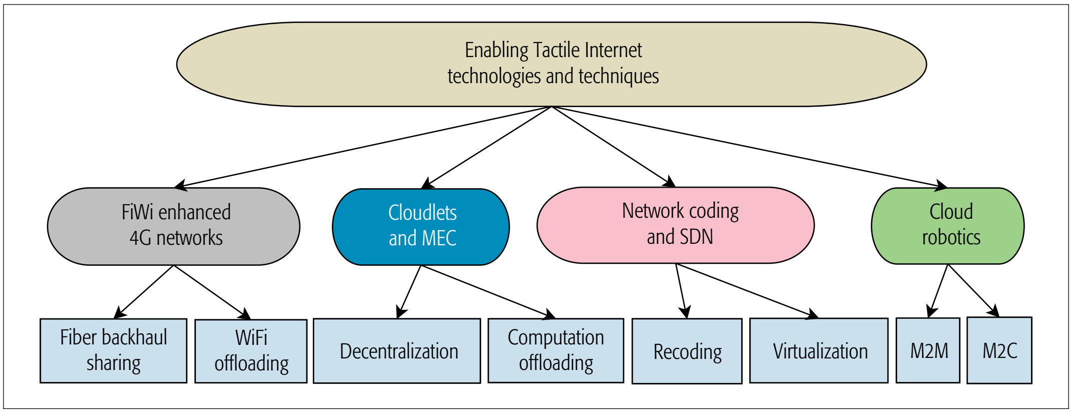


Figure 2. Taxonomy of enabling Tactile Internet technologies and techniques.

Beside protocol translation, the distributed processing and storage capabilities inherently built into R&F networks at the optical-wireless interface may be exploited for a number of additional tasks, for example, cognitive assistance, augmented reality, or face recognition and navigation for cloud robotics.

networks and capacity-centric FiWi broadband access networks based on low-cost data-centric optical fiber and wireless Ethernet technologies are removed. We elaborated on emerging trends and identified important open research challenges to unleash the full potential of FiWi enhanced LTE-A HetNets, including their convergence with other technologies and economic sectors for future non-incremental FiWi research. In the future, robots may become parts of our digital-age extended self just as online avatars are today. The adoption rate of low-cost domestic service robots, for example, robotic vacuum cleaners such as iRobot's *Roomba*, is growing rapidly due to the consumers' desire to save time spent in unpaid household work. Moreover, inexpensive general-purpose robots such as *Baxter* developed by Rethink Robotics are now able to learn new routines by simply guiding the robot arms through the motions without any need for programming.

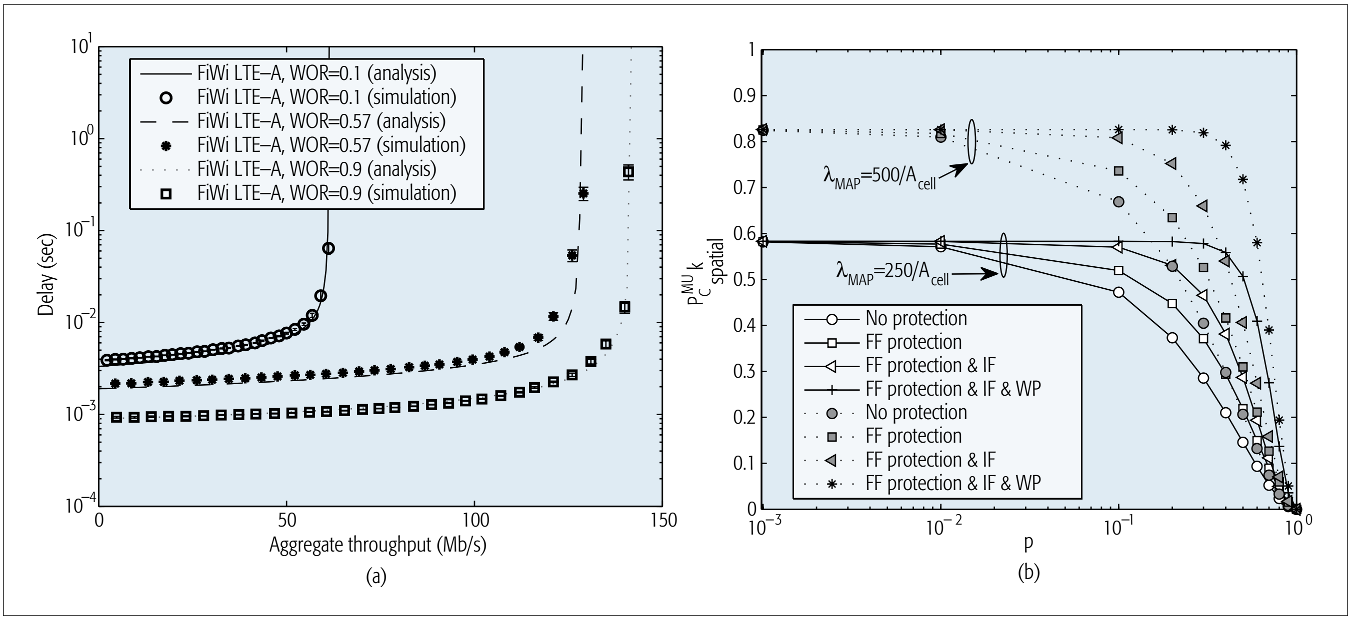
More recently, in [10] we elaborated on the role of FiWi access networks for conventional clouds and emerging *cloudlets* (i.e. decentralized entities at the edge of the Internet), thereby highlighting the limitations of traditional radio-over-fiber (RoF) networks to meet the aforementioned trend toward decentralization in future 5G networks. We revisited our early FiWi vision of the year 2008, where we advocated that the focus of access network research should shift from bridging the notorious first/last mile bandwidth bottleneck to the exploitation of distributed storage and processing capabilities, thereby creating unforeseen services and applications that help stimulate innovation, generate revenue, and improve the quality of our every-day lives. Toward this end, we proposed so-called radio-and-fiber (R&F) networks, which are based on decentralized (optical and wireless) Ethernet technologies and perform medium access control (MAC) protocol translation at the optical-wireless interface. Beside protocol translation, the distributed processing and storage capabilities inherently built into R&F networks at the optical-wireless interface may be exploited for a number of additional tasks, for example, cognitive assistance, augmented reality, or face recognition and navigation for cloud robotics. R&F may become the FiWi network type of choice in light of future 5G mobile networks moving toward decentralization based on intelligent base stations and cloudlets. In fact, as we shall see shortly, there is a growing desire among industry players to reap the benefits of mobile-cloud convergence by extending today's unmodified cloud to a decentralized two-level cloud-cloudlet architecture based on emerging *mobile-edge computing (MEC)* capabilities.

In the remainder of this section we provide a more detailed description of FiWi enhanced LTE-A HetNets, cloudlets, and MEC, as well as an up-to-date survey of other enabling technologies and techniques proposed for the Tactile Internet according to the taxonomy shown in Fig. 2.

FiWi Enhanced LTE-A HetNets

In [11] we investigated the performance gains obtained from unifying coverage-centric 4G mobile networks and capacity-centric FiWi broadband access networks based on data-centric Ethernet technologies with resulting fiber backhaul sharing and WiFi offloading capabilities in response to the unprecedented growth of mobile data traffic. We evaluated the maximum aggregate throughput, offloading efficiency, and in particular the delay performance of FiWi enhanced LTE-A HetNets, including the beneficial impact of various localized fiber-lean backhaul redundancy and wireless protection techniques, by means of probabilistic analysis and verifying simulation. In our study we paid close attention to fiber backhaul reliability issues stemming from fiber faults of an Ethernet passive optical network (EPON) and WiFi offloading limitations due to WiFi mesh node failures as well as temporal and spatial WiFi coverage constraints.

For illustration, Fig. 3a depicts the average end-to-end delay performance of FiWi enhanced LTE-A HetNets vs. aggregate throughput for different WiFi offloading ratio (WOR) values, whereby $0 \leq \text{WOR} \leq 1$ denotes the percentage of mobile user traffic offloaded onto WiFi. The presented analytical and verifying simulation results were obtained by assuming a realistic LTE-A and FiWi network configuration under uniform traffic loads and applying minimum (optical and wireless) hop routing. For further details the interested reader is referred to [11]. For now, let us assume that the reliability of the EPON is ideal, that is, no fiber backhaul faults occur. However, unlike EPON, the WiFi mesh network may suffer from wireless service outage with probability



(a)

(b)

Figure 3. FiWi enhanced LTE-A HetNets performance: a) average end-to-end delay vs. aggregate throughput for different WiFi offloading ratio (WOR); b) FiWi connectivity probability of a mobile user vs. EPON fiber link failure probability p.

10^{-6}. We observe from Fig. 3a that for increasing WOR the throughput-delay performance of FiWi enhanced LTE-A HetNets is improved significantly. More precisely, by changing WOR from 0.1 to 0.57 the maximum achievable aggregate throughput increases from about 61 Mb/s to roughly 126 Mb/s (at an average end-to-end delay of $10^0 = 1$ second), that is, the maximum achievable aggregate throughput has more than doubled. More importantly, further increasing WOR to 0.9 does not result in an additional significant increase in the maximum achievable aggregate throughput, but it is instrumental in decreasing the average end-to-end delay and keeping it at a very low level of 10^{-3} second (1 ms) for a wide range of traffic loads. Thus, this result shows that WiFi offloading the majority of data traffic from 4G mobile networks is a promising approach to obtain a very low latency on the order of 1 ms.

Figure 3b shows the beneficial impact of the various considered fiber-lean backhaul redundancy (FF: feeder fiber, IF: interconnection fiber between optical network units) and wireless protection (WP) schemes on the FiWi connectivity probability of a mobile user for a conventional two-stage EPON, whereby p denotes its fiber link failure probability. We observe that FF protection in conjunction with IF and WP are able to keep the FiWi connectivity probability of the mobile user essentially flat, though it is lowered when decreasing the density of deployed WiFi mesh access points, λ_{MAP}, from 500 to 250 in a considered cell coverage area of $A_{cell} = 3 \times 3$ km^2. Figure 3b clearly shows that the use of FF protection together with IF and WP enables mobile users to be reliably connected to FiWi for an EPON fiber link failure probability p as high as 10^{-1} and beyond, thus demonstrating the ultra-high reliability of mobile user connectivity to the FiWi access network, which is key to realizing the benefits of the aforementioned WiFi offloading and resultant very low latency performance of FiWi enhanced LTE-A HetNets.

Cloudlets and Mobile-Edge Computing

According to [12], only the concept of locally available cloudlets will enable us to realize the vision of the Tactile Internet. Even at the speed of light (e.g. in optical fiber access networks), 1 ms of round-trip propagation delay requires a cloudlet within 150 km. Cloudlets may be viewed as decentralized proxy cloud servers with processing and storage capabilities, just one or more wireless hops away from the mobile user. Cloudlet research has tended to focus on WiFi in the past, though recently there has been growing interest among cellular network providers. Figure 4 illustrates an example of cloudlet enhanced FiWi access networks, where cloudlets may be co-located with WiFi mesh portal points (MPPs) that interface with the optical network units (ONUs) of a shared fiber backhaul, as discussed above.

The importance of cloudlets can be seen in many end-to-end latency-sensitive applications such as augmented reality, real-time cognitive assistance, or face recognition on a mobile device. For instance, to manage and offload high volumes of data, Akamai recently developed the *Edge Redirector Cloudlet*, which is an early example of commercial applications of the cloudlet concept. In September 2014 the so-called *mobile-edge computing (MEC)* industry initiative introduced a reference architecture in order to list challenges that need to be overcome and facilitate the implementation of MEC [13]. MEC provides IT and cloud computing capabilities within the radio access network (RAN) in close proximity to mobile subscribers. MEC aims at transforming mobile base stations into intelligent service hubs by exploiting proximity, context, agility, and speed in order create a new value chain and stimulate revenue generation.

MEC is expected to enable a wide range of new services and applications. Among others, some important use cases include mobile unified communications, distributed content and DNS caching, RAN-aware content optimization, posi-

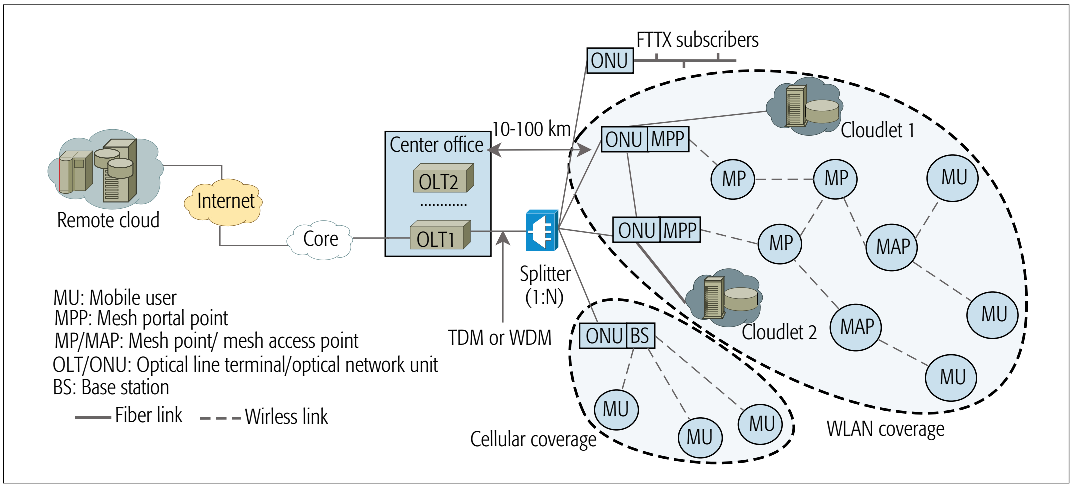


Figure 4. Generic architecture of cloudlet enhanced FiWi access networks for mobile-edge computing.

tioning over LTE (PoLTE), IoT, M2M, video analytics, augmented reality, and optimized local content. It uniquely allows mobile operators, service and content providers, over-the-top (OTT) players, and independent software vendors (ISVs) to tap into local content and real-time information about local access network conditions.

In [10] we elaborated on the deployment of both clouds and cloudlets in FiWi enhanced LTE-A HetNets to increase throughput, reduce end-to-end latency, and improve scalability by means of computation offloading. Recently, we built on this preliminary work by studying the coexistence of conventional broadband and MEC traffic in such a highly converged network. Our obtained results indicate that the use of cloudlets at the edge of FiWi access networks enables us to bring the vision of the Tactile Internet closer to reality by means of MEC, thereby achieving a significantly reduced end-to-end latency and an enhanced overall network performance. For illustration, Fig. 5 shows the achievable *average offload response time efficiency* for computation offloading onto cloudlets. In general, computation offloading should be performed if the time required to execute a given task on the mobile device locally is much longer than the response time of offloading the task onto a cloudlet. This time difference is referred to as offload gain. The average offload response time efficiency is defined as the ratio of offload gain and the response time of tasks that are locally executed on mobile devices. In the following, we assume that the data load of a computation task is fragmented into packets of fixed size and an application is subdivided into a number of fine-grained tasks. Figure 5 depicts the achievable offload response time efficiency for different offload packet sizes. We observe that as the offload traffic load increases gradually the overall response time efficiency increases. Figure 5 shows that for increasing offload packet sizes the average overall offload time efficiency asymptotically approaches 100 percent. For instance, for a typical case of N = 16 and an offload packet size of 1100.60 KB, the average overall offload response time efficiency equals 95.50 percent. This translates into a delay reduction of 95.50 percent compared to the delay obtained in a non-offloading scenario without MEC.

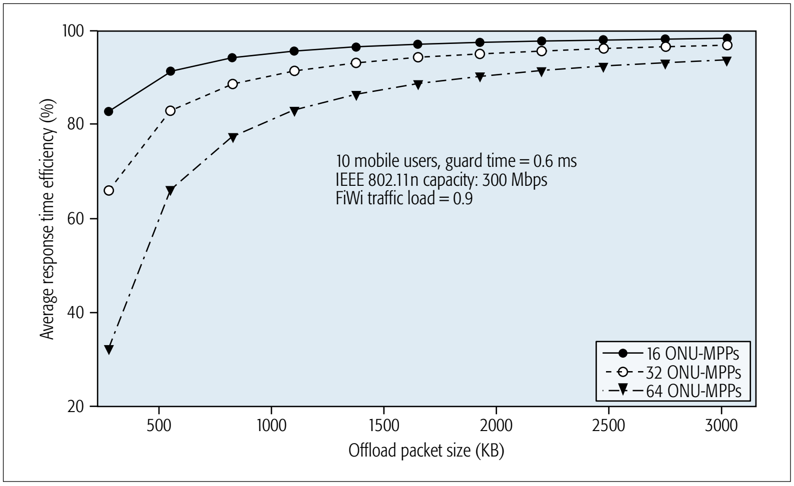


Figure 5. Average offload response time efficiency vs. offload packet size.

Network Coding and Software Defined Networking

In [14] the authors proposed the integration of network coding and software defined networking (SDN) as a viable approach to meet the Tactile Internet's very low latency requirement. The authors claimed that the extensive use of a more flexible network coding mechanism such as random linear network coding (RLNC) throughout the network can improve the latency performance and reduce the frequency of required packet retransmissions. RLNC is the most general form of network coding, whose main characteristics are recoding and a sliding window based operation. The recoding enables the so-called compute-and-forward approach, where each node in the network resets its coding strategy based on current network conditions for next-hop communication. The complexity of recoding is far simpler than alternative end-to-end (E2E) and hop-by-hop (HbH) coding strategies. This is due to the fact that with E2E coding each relay node needs to store and forward each successfully received packet, whereas with HbH coding each relay node performs full encoding and decoding of all incoming data packets. Conversely, unlike E2E and HbH coding which work

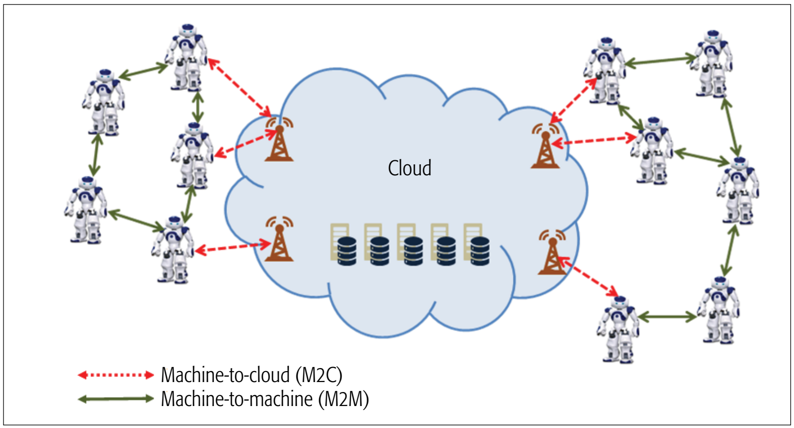


Figure 6. Two-tier cloud robotics systems architecture based on M2M and M2C communications.

on blocks of packets, RLNC applies the sliding window approach, which is beneficial for improving the end-to-end delay performance.

In order to provide deeper insights into achievable latency performance gains and validate their presented theoretical results, the authors implemented a network coding capable software router as a virtual network function (VNF). SDN and virtualization are commonly considered a promising approach to enable the flexible and automated deployment of VNF in networks. More specifically, the authors used ClickOS NFV platforms and deployed their software router on the Click modular router platform. The RLNC encoder, recoder, and decoder Click elements and fully-fledged compute-and-forward routers were developed by using the Kodo library and its built-in modules, respectively. Furthermore, 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 obtained results in [14] show that if the channel is error prone, RLNC achieves a lower latency than E2E and HbH coding. Moreover, 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 up to 6x and 16x.

CLOUD ROBOTICS

Providing robotic services to support daily human activities, especially for the elderly and persons with disabilities, through socially interactive behaviors has been an emerging topic in robotics research, where robotic services consist of systems, devices, and robots that provide the following three functions: sensation, actuation, and control [15]. In this study the authors presented a cloud-based robotic platform to continuously support human daily activities. Several key technological issues were identified for continuous robotic services such as multi-robot management, multi-area management, user attribute management, and service coordination management. Based on these issues, a cloud robotic based prototype was proposed, referred to as the ubiquitous networked robot platform (UNR-PF), which enables multi-location robotic services via distributed task coordination and control of multiple robots and sensor devices.

To extend the capabilities of both tele-operated and multi-robot based networked robotics, the authors in [16] proposed a cloud robotic system architecture that leverages the combination of an ad-hoc cloud formed by M2M communications among participating robots and an infrastructure cloud enabled by machine-to-cloud (M2C) communications between the robots and the remote cloud, as depicted in Fig. 6. M2M communications was used to enable a team of networked robots to complete tasks cooperatively in a distributed fashion by sharing computation/storage resources and exchanging information via the wireless communication network. M2C communications makes it feasible to learn from the shared history of all cloud-enabled robots. Furthermore, the authors proposed the use of gossip routing protocols for the considered two-tier M2M/M2C communications in cloud robotics. The potentially high latencies of distributed routing protocols based on gossip algorithms may be significantly mitigated by using the infrastructure cloud as a central super node for M2M/M2C communications. The authors also developed an optimization framework for task execution strategies that minimize the robots' energy consumption while completing their assigned tasks within a given deadline.

OPEN CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The Tactile Internet is still in its infancy. A number of open research challenges need to be tackled in order to realize its vision. Besides physical layer issues such as waveform selection and robust modulation schemes, intelligent control and user plane separation and coordination techniques will be vital to reduce signaling overhead and air interface latency. The design of advanced resource management techniques for the support of H2R traffic in R&F based FiWi access networks without degrading network performance is another promising area of future research. Furthermore, highly adaptive network coding techniques along with scalable routing algorithms may play a major role in providing QoS with enhanced security against malicious activities. Although network coding and SDN hold promise to reduce end-to-end latency in support of the Tactile Internet, further investigations are needed to explore the use of the sliding window approach in multi-path SDN based networks to also improve their throughput and resilience performance. In cloud robotics, the major challenges to be addressed include trust, privacy, security, as well as dependability and safety, given that networked robotic services are not limited to cyberspace but also interact with the physical world. Despite the wide deployment of industrial and service robots, real-time robot applications still suffer from several problems such as inefficiency in service completion. An exciting avenue for future work is the development of collaborative robots with advanced machine learning intelligence to perform collaborative work among truly autonomous distributed humanoid robots. Other important issues for the Tactile Internet include resource management and task allocation schemes (optimal online/offline scheduling), failure handling, mobility of robots, haptic feedback (multimodal or multisensory) based remote robot steering and control applications, as well as flexible service coordination among robots.

The overarching goal of the Tactile Internet should be the production of new goods and services by means of empowering (rather than automating) machines that complement humans rather than substitute for them [5]. Or as Nicholas Carr puts it: relying on computers to fly our planes, find our cancers, design our buildings, audit our businesses is all well and good, but what happens when machines fail and humans have become increasingly deskilled due to automation [17]? In the future, coworking with robots will favor geographical clusters of local production ("inshoring") and will require human expertise in the coordination of the human-robot symbiosis for the sake of inventing new jobs humans can hardly imagine or did not even know they wanted done. FiWi enabled H2R communications may be a stepping stone to merging mobile Internet, IoT, and advanced robotics with automation of knowledge work and cloud technologies, which together represent the five technologies with the highest estimated potential economic impact in 2025 [9].

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CONCLUSIONS

The Tactile Internet will be centered around H2M communications by leveraging devices that enable haptic and tactile sensations. Similar to IoT and 5G, it demands very low latency, ultra-high reliability, H2H/M2M coexistence, integration of data-centric technologies, and security. As the power of machines increases, the Tactile Internet should help complement humans rather than substitute for them, thus empowering them by providing a growth path based on increased output rather than reduced inputs due to automation. In particular, research on the design of future wired and wireless access networks based on decentralized cloudlets and MEC capabilities will be essential for the coordination of the human-robot symbiosis via FiWi enabled H2R communications. This article comprehensively surveyed the recent progress on FiWi enhanced 4G mobile networks, cloudlets, MEC, network coding, SDN, and cloud robotics, with a focus on their significant latency and reliability performance gains.

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