INVITED PAPER

Leveraging Tactile Internet Cognizance and Operation via IoT and Edge Technologies

This article presents novel techniques for Cloudlet-based cyber foraging to project how Tactile Internet interactions could benefit from IoT contextualization.

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ABSTRACT | The Tactile Internet (TI) is building on the premise of remote operation in perceived real-time, and enables a plethora of applications that involve immersive interactions. As we build a future for globalizing skills, delivering haptic feedback across continents, and immersing users in remote environments, we are faced with significant challenges in understanding the context of Tactile Internet interactions, which we refer to as *tactile cognizance*. The challenge of understanding a remote terminals' context impacts not only the quality and depth of haptic feedback, but our ability to deliver perceived real-time operation. That is, as we develop AI techniques to compensate for the inevitable delay in remote operation, we need more information about a terminal's context and interactions to improve our prediction of movement and feedback. The Internet of Things (IoT) is promising to interconnect billions of sensors, and augment multiple tiers of cognition to expedite and fine-tune sensory acquisition from heterogeneous contexts. In this paper, we will survey recent developments in the IoT, and novel techniques for cloudlet-based cyber foraging (i.e., edge computing) to project how Tactile Internet interactions could benefit from IoT contextualization. We present a taxonomy of edge IoT systems designed for rapid data acquisition, with an emphasis on systems that prioritize stringent reliability and latency mandates. This paper builds on edge computing techniques to propose a framework for multi-tiered cognition in the Tactile Internet to feed its signaling systems, and how future TI codecs could embed contextual information in haptic feedback.

KEYWORDS | Cloudlets; edge computing; Internet of Things; Tactile Internet Cognizance; Tactile Internet

I. INTRODUCTION

What is within your *remote* grasp? The Tactile Internet (T1) is pushing the envelope in democratizing skills and developing technologies that will enable omnipresence and exchange of tactile interactions across the globe. This premise is built on synergistic advancements in communications, haptic-technologies and artificial intelligence.

Since Fettweis instigated the premise of the Tactile Internet, and the many facets of its applications [1], many researchers have joined efforts to realize this far-fetched architecture [2], [3]. The TI is defined by the IEEE P1918.1 Tactile Internet standard working group as: "A network, or network of networks, for remotely accessing, perceiving, manipulating or controlling real or virtual objects or processes, in perceived real time by humans or machines," which is the standing definition [4].

Simsek *et al.* [2] present a thorough investigation on the premise of the TI and how recent advances and projected developments in 5G technologies will enable this architecture. Chief among them are the ever-increasing capacities of cellular networks with massive multiple-input–multiple-output (MIMO), as well as other wireless and wired communication modalities, that are experiencing multifold improvements in three major factors: line rates, end-to-end latency and communication reliability [1], [2].

These three pillars of TI communication could be realized over a multiplicity of network modalities. High data rates, once exclusive to fiber optics, are now

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being nearly matched by new developments of wireless communications in the 300-GHz band via CMOS transceivers [5]. Visible light communication systems are miniaturizing transceivers and introducing significantly higher data rates than (currently) traditional wireless RF communication [6]. Jalajakumari *et al.* recently introduced an integrated digital-to-light converter capable of reaching 365 Mb/s with bit-error rates as low as 10^{-3} [7].

Even underwater communication, via acoustic waves, is witnessing recent breakthroughs over inherent limitations. That is, given that acoustic communication stood as the main contender for long-range underwater communication for a long time, it was doomed by limitations within 20 kHz due to damping attenuation at higher frequencies. Recently, Shi *et al.* introduced a new modality for overcoming this challenge by employing additional spatial degrees of freedom in data transmission, by exploiting orbital angular momentum of acoustic vortex beams to increase data transmission rates [8]. Moreover, new modalities such as magnetic induction are promising newer alternatives to underwater communication, with favorable properties in higher data rates and stealth operation [9].

Advances in communication are not the sole driver in this undertaking. Recent developments in haptics are enabling many services where remote immersion of users is now possible. This paper presents the notion of tactile cognizance, and investigates new developments where IoT input could be fused with input from haptic probes that *touch* a given surface to capture vibrations via minute accelerometers, augment that with responses from high-fidelity microphones, and fuse these with images captured by cameras to yield high-end multimodal surface material classification [10].

In fact, Alt and Steinbach published a patent on visuo-haptic sensors, which are able to manipulate a deformable object and report its surface properties [11]. A thorough survey on principles and developments in haptic communications is presented in [12].

Such advances in haptic sensing, cognition and control, are a significant leap in the efforts to realize remote robotic arms that could remotely interact, and report on properties of remote objects and surfaces, with high accuracy. Even to compensate for current limitations on network bandwidth, and in an attempt to prioritize (i.e., expedite) haptic traffic when multimodal capturing is required, Cizmeci *et al.* present a novel multiplexing scheme that avoids jittery transmission of haptic feedback [13]. They present a scheme whereby transmission rates are constantly monitored to detect sudden fluctuations (mainly drops in data rates), to adjust traffic management and prioritize haptic response delivery, which may be hampered by the transmission of video and audio components of the remote capture.

With such advances over different communication modalities, and successive improvements in computational power, there is significant evidence that the TI could soon

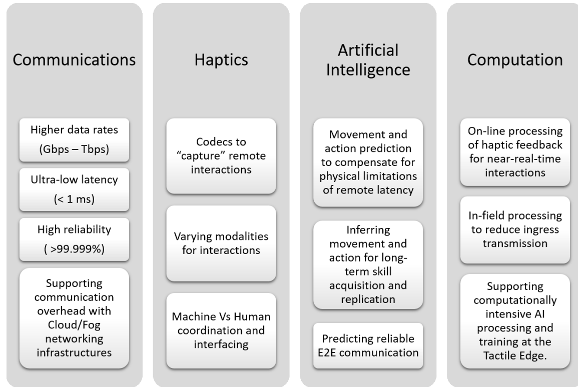

Fig. 1. ***Challenges of realizing the Tactile Internet span many domains, summarized here to highlight some of the immediate research challenges.***

be a reality. However, the challenges facing TI development span a multiplicity of research fields. In Fig. 1 we present four of the major categories of challenges facing TI realization. Most notably, the stringent requirements under each of them necessitate synergy in our collective development efforts. While we may have a good idea about how some of these challenges could be tackled, we are investigating advances in cross-technology developments that will catalyze TI development.

These operational requirements often challenge the status quo in multiple fronts. That is, ensuring a submillisecond end-to-end latency is not simply a communication challenge, but a computing one as well. Do we have the processing power, on both end terminals and network components, to handle traffic with such stringent latency and reliability metrics? If these conditions are violated beyond 5 ms, then audio–visual interactions become out of sync; beyond 10 ms, the famed cyber-sickness phenomenon will mar simulators and Augmented Reality systems [1]. These challenges test the limits of the status quo and dictate novel developments on multiple fronts. The question being, when would these requirements be met to enable the TI architecture?

For example, the doubling of computational power predicted by Moore’s law every 18 months—a long-standing staple since the 1965 and 1975 papers—is currently[1] being scrutinized as we reach new road blocks in miniaturization [1], [2], [14]. Theis and Wong [14] argue that we are not diminishing the prospect of increased growth in computing power, but merely redirecting research at new frontiers, shy of mere miniaturization that is reaching feasibility and economic roadblocks.

This is evident in new approaches to boosting computational capacity per unit area, as in the Highly Adaptive Energy efficient Computing (HAEC) box vision, able to sustain over 1 billion computing nodes within a 10-cm^3

[1]The scrutiny facing Moore’s law is as old as the law itself. Every few years/months some researchers argue that we have hit the limit, and then a new breakthrough sustains Moore’s prediction further [14].

space, presented by Fettweis *et al.* [15] and elaborated upon in [2]. The HAEC box is based on ultra-short range optical wireless communication between chips inside a cluster of computing nodes, alleviating challenges with bus-based I/O communication within a closely stacked chassis.

Evidently, the incessant consumer/service-driven demand for higher data rates, more immersive experiences, and seamless integration of all of these services with our tangible world, are mandating a new approach to how researchers and users evolve with the Internet. While researchers are heavily invested in improving service delivery, quality of service metrics and tailoring quality of experience to an every growing set of diverse users, we have our eyes focused on what new advancements in tomorrow's communications and computing could offer us.

The remainder of this paper is dedicated to the exploration of what current technologies are offering that could leverage the TI ecosystem and expedite its design and dissemination. A comprehensive survey of what the TI can deliver and its coupling with 5G developments is already well covered in [2], as well as [1] and [3]. The interested reader will find a wealth of information on potential use cases in these aforementioned three references, as well as new insights drawn from the larger community presented in [16].

The specific emphasis of this survey is on the classification and synergy of recent developments in the sphere of the IoT and Edge Computing, that could improve TI operation in two major dimensions, namely: 1) situational awareness/contextualization at the tactile edge; and 2) architectural support at the various tiers of TI operation.

The goal of this survey is trifold. First, we aim to present and highlight the benefits of integrating tried-and-tested techniques driven from parallel research communities. Second, we hope for this work to instigate a larger discussion across researchers in closely related fields, one that would shed light on potential opportunities for synergy in development and coexistence. Third, highlight voids and challenges in future networking paradigms that would potentially coexist with the TI, and offer early suggestions for coping and managing this coexistence towards mutual integration and progression (for example, with information centric networks).

The remainder of this paper is organized as follows. Section II elaborates on what the environment of TI encompasses, and its impact on operation across the different tiers of TI operation. Section III presents the notion of TI cognizance and argues for operational gain in building on neighboring infrastructures. Sections IV and V present insights on how developments in next generation networking infrastructures could aid TI operation at the edge and core, respectively. A primer on TI coexistence challenges and potential gains is presented in Section VI, and we highlight future areas of synergy with novel architectures in Section VII.

II. TACTILE INTERNET OPERATION AND IMPACT OF ENVIRONMENT

The TI is centered on remote operation of machines, as well as immersive experiences that bring a remote environment into the controllers' grasp. An immersive experience inherently implies that most of the relevant sensory details in a remote environment are conveyed to the TI user/operator.

However, as we attempt to develop codecs to encompass haptic feedback, an important line has to be drawn between environmental factors that might be measurable/attainable via other infrastructures and specific haptic data that is best suited to haptic sensors. So far, the latter has been the focus in haptic codec development for TI [17].

By environmental factors, we refer to the broad spectrum of devices, humans and weather factors that might interfere, both positively and negatively, with TI operation. For example, these include aid/intrusion from other (on-site) operators, range of motion of neighboring machines, humidity/clarity of vision at the Tactile Edge operation zone, in addition to even medium access contention over communication hops.

We hereby argue that significant environmental data could be leveraged via IoT architectures that are growing in abundance and performance. More importantly, the operational environment of TI could be significantly impacted by environmental factors that are not properly accounted for, or altered post-deployment.

As we investigate the potential impact of these neighboring elements, we need to define what must be encompassed in codecs, what should be probed from non-TI resources (e.g., stationary cameras at operation site) and what should be encoded in TI operation policies, for contingency planning (e.g., failure/delay of local Cloud-access point).

In the remainder of this section, we first explain the stages of a TI in operation, in reference to the layers depicted in Fig. 2. We then elaborate on environmental challenges that affect TI operation and conclude with the definition and overall challenge of developing TI cognizance.

A. TI in Operation: Layers and Components

To enable a comprehensive study of where and how environmental factors could impact TI operation, we build on the preliminary architecture envisioned for TI, as depicted in Fig. 2. We will then build towards more recent developments in TI architecture design, pertinent to developments in the IEEE P1918 Tactile Internet Standard working group, which are depicted in Fig. 3, in a progressive breakdown of TI components and layers.

Potential architectures of the TI have been explored in earlier proposals, such as Fettweis' early exploration of what the TI can achieve [1], and the 5G oriented architecture presented by Simsek *et al.* in an elaborated study [2]. Further TI proposals typically followed the same overall

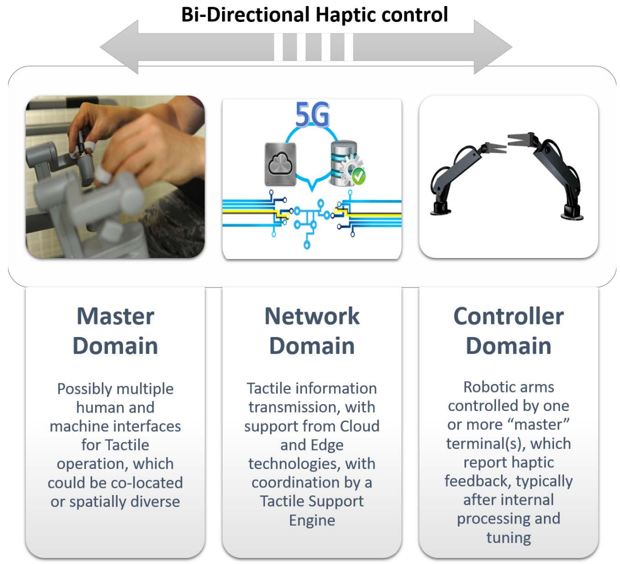

Fig. 2. ***Early design of a Tactile Internet architecture in operation, identifying three major components. This has formed the basis of discussions on TI development in [2], [3] and [16], and early stages in architecture development in the IEEE P1918 Tactile Internet Standard working group. The current architecture design being incorporated in the standard spans more components and levels and is further elaborated upon in Fig. 3 and Section II.***

architecture, such as [3] and [16], which is depicted in Fig. 2.

The main takeaway was adhering to a feedback loop between commands that traverse the network from the master domain to the controller domain. Then, haptic feedback is registered, analyzed, encoded and pruned by devices on the controller domain, which is then transmitted back via the high speed backbone towards the master domain for deciding on the next action.

Ultimately, communication between the tactile operator(s) and established controller(s) are carried over ultra-low latency links, which either depend on circuit-switching methods (physical and virtual), and are aided by tactile support engines, or leverage developments in 5G and massive MIMO that promise to meet such requirements.

As the architecture design and potential use cases were further developed, it became evident that more scenarios for human-to-device and device-to-device may arise, which dictate a more granular look at how control, tactile operation and communication logistics may eventually manifest [16].

For example, how would the remote operation of one unmanned aerial vehicle (UAV) affect its swarm as they navigate an unfamiliar terrain? If the operator is only concerned with that single UAV, how can the actions of other UAVs unexpectedly affect it? If other operators are in fact managing the other UAVs, how will they interfere/aid this specific UAV, and overall swarm operation?

More interestingly, how would UAVs that operate via local or remote control of other machines cooperate or interfere with this human-operated UAV? What part of its tactile feedback is reported to the human versus other UAVs? How would codec design incorporate multi-operator dissemination, still under the stringent communication and reliability requirements?

These questions and use cases necessitated a dual-pronged approach to architecture development. First, the specific layers need further dissection to enable fine-tuned policy design. Second, the support of cognitive modules are solicited at different stages in TI operation to leverage performance and responsiveness, while maintaining cooperation across multiple controllers.

To this end, Simsek *et al.* presented an example for latency objectives per TI layers, to attempt to achieve a sub-1-ms delay from end-to-end [18]. This architecture envisions the support of a mobile edge cloud system that will mediate communication between sensors and actuators across the ends of a TI operation. In this stringent scenario, they argue for an expected 100-μs delay over the air interface (mostly propagation delay).

While this proposal highlights the potential gain in responsiveness when edge cloud architectures are employed, the impact and design complexity of adopting cloud architectures is significant [19] and requires significant exploration for TI operation. More importantly, it mandates a specific study of where (which components) and when (times/scenarios) it would leverage TI operation.

To account for environmental factors at the tactile edge, as well as variations in policies governing TI operation across the layers, we present an extended view of the TI architecture in Fig. 3. Each of the three stages of TI operation will be explained in the remainder of this section.

B. At the Tactile Edge

The tactile edge encompasses the sensors, actuators, computing and communication resources deployed at the remote site where tactile operation is controlled. In Fig. 3, the components of a tactile edge are grouped, specifically the three left-most phases. It is important to note that this is not a physical separation in hardware, but rather a logical classification of which components of the TI are engaged at any stage in remote operation.

Many technologies need to cooperate to realize tactile operation at the edge, and there are indeed many proposals for incorporating mobile edge cloud architectures, tactile codecs, techniques from dynamic wireless sensor networks [20] to manage efficient sensing, as well as IoT devices that could be probed to augment data collection from haptic sensors. For example, Simsek *et al.* [18] and Ateya *et al.* [21] argue for the operational gain in offloading localized TI processing at edge resources, specifically, engaging edge cloud technologies to aid in sensor fusion, data aggregation, as well as codec processing. More importantly, as TI operation often mandates stringent

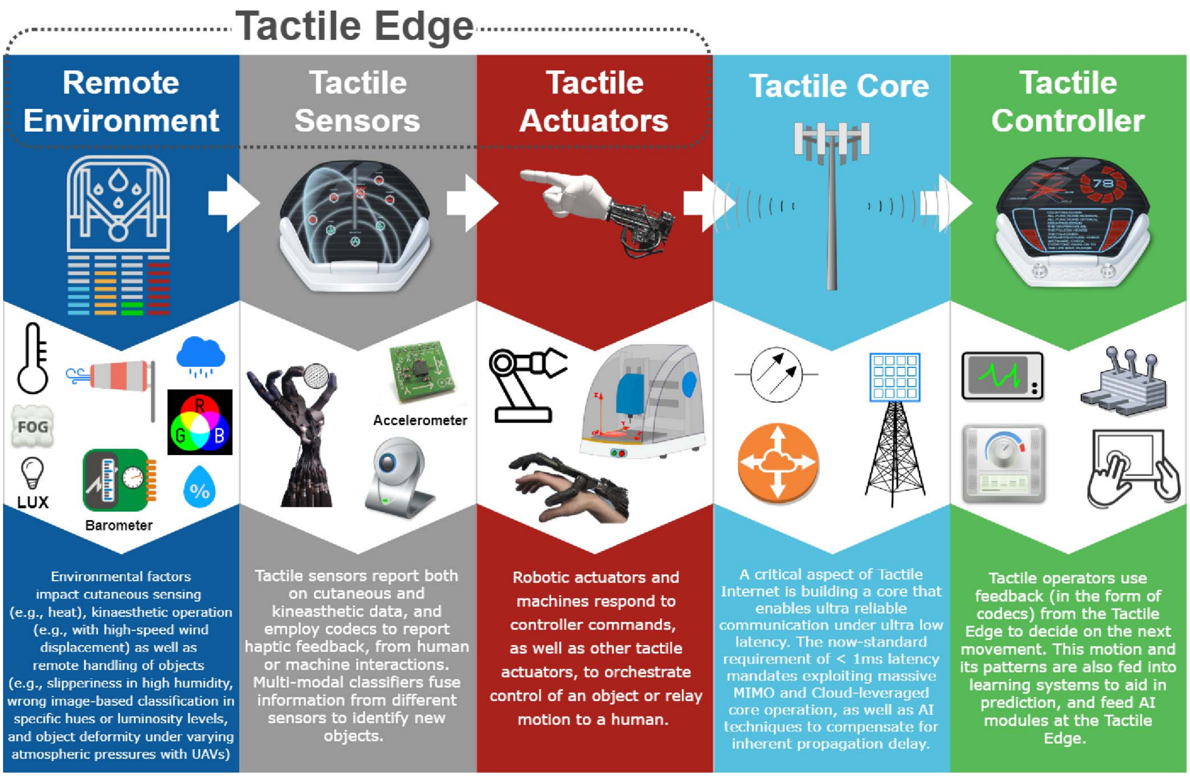

Fig. 3. ***Phases of Tactile Internet operation, main components, and functional requirements at each stage. The flow of input goes right to left, and then control commands go back through the chain right to left: Controller → Core → Edge.***

latency requirements, there is an important role for AI algorithms to record, learn, predict and augment control commands in the case of delay or jitter from the Tactile operator [1]–[3].

That is, observing that there are often repetitive patterns for remote operation and human control [1], [3], [12], [17], [22], there is a strong need for building adaptive learning algorithms under the broad umbrella of AI systems to *predict* what the next movement would be from the remote operator, and step in if it does not get reported in time [26]. While this may seem far-fetched, there is significant evidence that online (real-time) learning systems are able to accurately predict a high percentage of human motion, especially in repetitive or constrained environments (e.g., industrial automation and repair) [27].

We argue that environmental factors at the edge play a significant role in how quickly such AI systems could converge and reach steady state operation. For example, varying weather conditions will significantly influence image-based classification systems that infer action based on current visual analysis in a given field [28]. More importantly, as TI systems at the edge attempt to employ learning schemes that could potentially probe local repositories of data/actions, various environmental factors and cross interference from other TI components (from other remotely operated systems) will increase the complexity of input scenarios to such learning systems.

C. At the Network Core

While the challenges with 5G communication for TI have been introduced in [2], [3], [16], [31], [32] and others, there are significant challenges in understanding the impact of environmental factors in TI communication from end to end.

First, as TI components intercommunicate at the edge, many protocols that are designed for short-range communication are impacted with significant interference, especially in the ISM band [33]. The rise of short and medium range communication techniques across many networking paradigms [34] is further aggravating medium contention as we pull/push data from the TI edge.

Medium access control (MAC) schemes have been heavily investigated, both in M2M scenarios [35] as well as proposed deployments in narrowband IoT (NB-IoT) [36]. NB-IoT is envisioned as the cellular solution to direct communication with IoT devices in next generation cellular networks and is under significant development and standardization efforts by the 3GPP body [37]. A recent attempt [38] proposes a hybrid scheduling-based protocol MAC on Time (MoT) that guarantees the delivery of all uplink packets in the network and addresses several of the challenges of TI.

However, these studies have been mostly oriented around low-power devices that exist at the edge of the network and are often energy constrained. In the TI, with stringent latency requirements, we are in need of elaborate studies on the impact of medium access contention and scalability of TI communication protocols, as they probe TI edge components. Even if we opt for wired communication to alleviate MAC challenges, we need to investigate challenges with scalability and design complexity as TI systems become more immersive and multifaceted, that is, when TI systems incorporate a significant number of communication links to interconnect complex architectures at the edge and the core, especially with device-to-device (D2D) communication [38].

The interested reader may refer to the survey by Tehrani *et al.* for spectrum management challenges in the licensed spectrum [40], and the overview on challenges in LTE operation in the unlicensed spectrum [41], a direction adopted by proprietary standards such as *Multefire* [42].

As the communication challenge magnifies for ingress traffic flowing through the core, environmental interference becomes another risk factor in adding to delay. That is, neighboring communication flows, as well as competing TI end-to-end communication lines that overlap from a given operator to the same TI edge, will present interference and inherent delay as the network scales [38], [43].

D. At the Tactile Operator

The quality of experience of the tactile operator, as she is immersed in remote operation, is strongly correlated with QoS measures for control and communication, as well as relaying as much context information as possible from the TI edge. This is inherent in any teleoperation scenario, and has been heavily investigated since the 1980s [23], with significant assumptions being made on what data reporting would suffice to relay an overall adequate experience [22].

However, the TI edge is getting increasingly complex with different interactions and often could be intruded/violated by other humans/machines/systems. This raises significant concerns about the minimal amount of information about the current operational environment that would facilitate acceptable TI operation. To this end, we argue that TI systems must incorporate significant measures of tactile cognizance, which we further elaborate upon in the following section.

III. TACTILE INTERNET COGNIZANCE

As we embark on developing a new technology for global communication, we must learn from the lessons of its predecessors. The IoT is facing significant disparity and sporadic development in silos and verticals [44], with little regard given to synergistic development and cooperation [45].

Early standardization efforts are key in developing homogeneous and scalable architectures, and the TI community realized this and enacted a strongly supported working group under the IEEE P1918 Emerging Technologies Committee (ETC) [4]. The working group is vested in

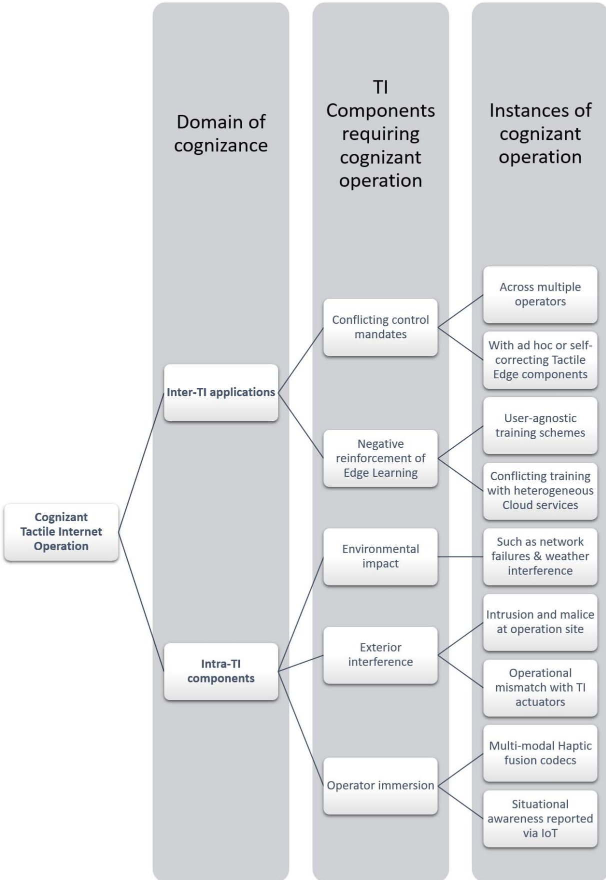

Fig. 4. ***Taxonomy of challenges to consider in developing TI cognizance. It is important to distinguish cognizance of parallel TI applications that are sharing the same backbone/edge infrastructures, and TI cooperation between operators on a single application. Both cases impose critical challenges in coexistence and potential hindrance, which should be explored under TI cognizance research.***

developing a progressive architecture to encompass different TI use cases and scenarios, building on developments in parallel technologies.

To augment these efforts, we propose the development of a dedicated track of studies on TI cognizance, that is, exploring the interactions between TI components and the surrounding environment, as well as interactions between TI components and coexisting network infrastructures and applications. We present in Fig. 4 a primer taxonomy of challenges in TI cognizant operation, and the factors that should be considered in both inter and intra-TI operation.

The notion of TI cognizance has two simple goals: First, to relay all relevant operational, environmental and situational data to the operator to improve their command and immersion in the remote environment; namely the tactile edge. Second, to improve the quality of training and learning for all assistive components at all stages of TI operation, that is, to harness more contextual information aimed at improving the training of AI modules at cloud access points, both at the edge and network core.

The gains of the first goal are clear, more smooth and informed control by operators. This leads to higher adoption rates and faster dissemination of skills around the globe. The second goal aims at improving TI speed, accuracy, rate of convergence, all while reducing time to deployment. The economic as well as social impacts of expediting efficient TI delivery are significant [1], [31].

Thus, it is critical to gather information about the context of any TI operation to provide and address these two goals. However, this overhead should not be left to the TI network to handle, nor to overcomplicate codec design. In fact, we argue for dissemination of contextualization tasks across currently available technologies. With the abundance of technologies that would cohabit the TI at the edge and core levels, we can significantly leverage TI cognizance without slowing down TI operation.

We have come far from when the notion of remote telepresence with the operation of distant robots has been presented as early by Minsky [23]. Recent development efforts with haptic communications [12] have been augmented with attempts to employ technologies such as network coding and software-defined networking [30] to leverage TI operation. In the next two sections we survey some of the prominent technologies that could aid TI operation at the edge and core, respectively.

IV. TACTILE INTERNET COGNIZANCE AT THE EDGE

We survey recent developments in technologies that will enable and advance Tactile Internet interactions. The core of backbone communications (e.g., on 5G advancements) is covered in this special issue at large, and more specifically in [2], [3], and [16]. Our emphasis in this section is on anchoring Tactile edges and networks in neighboring technologies.

It is important to note that advances in robotics and remote automation via cloud architectures, including crowd-sourcing human experience on robot control and automation, as well as access to large data sets of training and operation, are proving fruitful in many applications [27], and are well suited to aid tactile operation at the edge.

A. Role of IoT Devices

The Internet of Things can significantly leverage TI operation on multiple levels. While it is true that IoT operation is far from standardized, and the current silos in operation significantly hinder their scalability [45], [46], having a concrete common denominator such as a TI architecture can synergize many IoT developments. To that end, we envision IoT advancements as aiding TI operation both in TI-edge intercomponent communication, as well as TI cognizance.

There is a significant advantage for lightweight sensing architectures that are heavily researched in IoT. For example, we present a dynamic sensing architecture that enables individual sensors to form sensing systems on demand, and associate with neighboring IoT nodes based on the required data [47]. In such an architecture, TI sensors and actuators could probe dynamic sensing components as needed to augment their data inputs, or solicit data to support failed sensing components.

There is significant work carried out on IoT interoperability, both on the semantic level of data collected [46], as well as fusion of data and information sources from crowd-solicited resources [45]. Thus, TI edge components are able to probe local IoT data repositories to improve TI environmental and operational cognizance, as well as compensate for TI operational failures and stabilizing sensing performance [48].

More importantly, TI operators could leverage IoT resources in the field of operation to further improve their immersive experience. This is attainable via crowd-solicited sensing architectures that are ever-growing in today's urban environments [49], [50].

Furthermore, there is a significant body of research on incentivizing crowd sensing systems to provide higher quality of data [51], [45]. In fact, new measures of quality of data, quality of resources, and quality of information are elaborated upon in [45] to highlight the heterogeneity of IoT resources, and the potential gain in establishing standardized benchmarks for the QoD each resource could provide.

Recent studies on the potential gains in carrying out Edge analytics before disseminating such data are gaining prominence [50], and are coupled with studies on developing QoX measures that will aid better data and performance calibration [52].

These IoT components could interact with TI systems in a multiplicity of models, and we could envision the Edge Cloud architecture as a mediator, in addition to direct communication protocols that are designed to be low-power and extendable such as ZigBee [53]. The important condition to maintain here is ensuring that IoT interactions with TI components will not drag TI performance, as IoT systems are not designed with the aforementioned stringent requirements on latency and reliability. The interested reader may refer to the elaborate surveys on IoT operation presented in [44] and [54].

B. Cloudlets

Satyanarayanan has led the research community in many efforts for what he dubbed cyber-foraging in the mid 1990s [50]. He advocated for the notion of offloading computationally intensive tasks on resources that are not necessarily coupled with the host device and ensuing Cloud technologies followed his vision and direction.

While cloud computing paradigms have significantly evolved over the years, it became evident that time critical applications could not afford the round-trip delay of offloading a computational task and awaiting the response from a remote VM on a data center. Thus, the notion of mobile edge computing and edge analytics advocated for the adoption of cloud-outlets (cloudlets) that are inherently deployed closer to the user, and act as intermediary computing and storage systems that could leverage performance and offer more rapid access to elastic resources [50].

TI operation could significantly leverage its performance if tactile edge environments are coupled with cloudlet deployments. We envision two scenarios of potential gain. The first scenario is offloading policy management and intra-TI edge component communication on nearby cloudlet resources to manage machine-to-machine and human-to-machine cognizance and improve interoperability across remotely controlled tactile edges. Second, we argue that AI training modules would be far more contextualized as they are brought closer to the edge where remote operation is taking place, thereby using IoT resources as well that could enrich the learning algorithms with contextual input, as well as specific the tunable parameters of the training models to the actual region of operation.

The rise of research on mobile edge computing [55], [56] will enable a fine tuned model of operation for TI interactions, especially as we envision TI operation in nonstationary settings. Furthermore, mobile edge computing architectures are inherently better tied with cellular systems, making possible integrations with 5G operation and future cellular networks more seamless. A possible route for this integration is enabled via network function virtualization (NFV), and there are currently many efforts exploring such synergy at the edge of cellular networks [57].

A final cautionary note, indeed a common caveat, is the security challenge of interoperability with cloud architectures [58]. As more and more devices become cloud dependent, with an anticipated explosion in the number of cloud-leveraged services and architectures [61], we are ever in need of more secure coupling schemes for sensitive architectures such as the TI with abundant and powerful systems such as MEC.

V. LEVERAGING TACTILE INTERNET OPERATION AT THE CORE

While most of the operations of the core are currently explored in 5G developments, it is worth noting that new research frontiers are opening up due to progressive architectures, such as the TI.

The challenges of TI communications have been among the first to garner interest in the research community. In fact, the TI emerged as a prime application for 5G applications, as many researchers questioned the need for massive communications at such high data rates [1]–[3], [26], [31].

The challenge of routing over a packet-switched Internet paradigm was tackled by Farhoudi *et al.* [33]. They presented a multiplane routing scheme that attempts to consolidate different aspects of an inherently IP-based Internet backbone, to enable network-wide path variations in delivering haptic feedback. While the approach they presented is largely based on a binary LP formulation, with a specific imposed restriction on routers catering to two separate traffic patterns (tactile and all others), with separate queues and buffering systems, there is merit in attempting to piggyback a solution on the current Internet infrastructure.

Recent developments in multiaccess edge computing are proposing to merge cloud services with network edge architectures in 5G. Talib *et al.* present a comprehensive survey of such orchestration attempts, and highlight the potential gains in supporting mobility and native IoT and M2M cooperation at the cellular network edge [57].

In addition, current testbeds are being developed in King's College London [26], with Cloud-RAN and Edge-Cloud architectures being tested for insights into TI development. Moreover, recent attempts at leveraging narrower Fog architectures that are closer to the region of demand have spurred interest in aiding core network operations via the notion of fog-leveraged radio access networks (F-RAN) [58].

However, the main goal of these architectures has been the balance of resource solicitation from F-RAN and other cloud architectures, to offload RAN overhead. Thus, the broader challenge of resource management governs what is to be allocated locally in the RAN and what should be offloaded. Recent developments in radio resource management and allocation under multiple access schemes in LTE-A have been probed by Ajaz [32]. Specifically, a novel heuristic has been developed to address power and resource block allocations using a low-complexity heuristic, to handle both uplink and downlink haptic data communication in TI applications.

Managing the overhead in cloud leveraging systems has been the focus of many research efforts, including seminal work by Xu *et al.* [19]. One of the many challenges, in addition to the evident time delay in soliciting and transferring tasks to the cloud(let) and back, is the trustworthiness and security of such a mechanism [59]. The cellular system is by large a highly monitored environment, with clear fingerprinting mechanisms and authorization steps. However, many of the accessible cloud(let) systems, especially at the edge, may neither have the scrutiny nor the fingerprinting mechanisms maintained in cellular environments [60].

VI. TACTILE INTERNET COEXISTENCE WITH NEXT GENERATION NETWORKING PARADIGMS

As a new paradigm, the TI will build on the premise of URLLC, as well as developments in the broad spectrum of telecommunications, computing and human–computer interaction. Inevitably, many of these advances are shifting our paradigms in communication, and it is pivotal to plan for, as well as drive, some of these developments towards synergistic operation with the TI. In this section we will survey some of the prominent networking technologies that are changing our paradigms of communication and discuss their relevance to TI development.

A. Software-Defined Networking (SDN)

The operational mandates of tomorrow's Internet are straining our physical infrastructure, especially at the core of the Internet backbone [64]. As our routers and switches face mounting difficulties in meeting rising QoS expectations, new models of development in SDN are promising to decouple the control plane from the data plane, hoping for a more malleable and agile infrastructure [61].

The TI architecture is built on the notion of an expansive infrastructure that will scale with functionality and enable a multitude of E2E communication paths, based on availability of URLLC guarantees and need for parallel connections between Tactile edges. While Arslan *et al.* have presented frameworks for leveraging cellular operation via SDNs, we mainly focus on the functional gain in supporting TI components (e.g., the tactile service manager and the network domain) in improving their elasticity and agility to support ever-changing TI requirements. SDNs could play a major role in realizing this much needed TI-infrastructure agility, and there are efforts underway in the TI P1918.1 standard working group to investigate the premise of SDN development in light of the emerging TI architecture.

B. Nanonetworks

As one of its major players, the tactile edge is mainly composed of sensors, actuators and haptic receptors that are able to immerse a remote user in a given environment. Recent developments in nanonetworks, especially in the biological spectrum [63], will enable a number of use cases that could improve medical TI applications. While communication between sensors, actuators, and other devices at the tactile edge may comprise larger nodes, there is hope in bringing inherently accurate robotic and machine-controlled interactions on the molecular and cellular levels. The rise of nanocommunication, both as an enabler of short range communication in/around the human body, as well as a carrier for delicate health-related data from embedded/worn sensors, is promising significant advancements in the realm of medical TI operation.

For example, remote control of implanted nanoactuators and networks for medical operations could bring TI into the human body, with significant gains in reduced errors in operation and democratizing very rare surgical skills [68]–[70], [63]. As we continue to study the potential of molecular communications, and the remote networking of implanted medical sensors, we could further extend TI operational use case to nanoscale surgeries that are of significant scarcity.

C. Information-Centric Networks

The past decade has witnessed a significant number of efforts directed at changing the Internet paradigm from a host-centric to an information-centric one. The main driver has been the ever-increasing impact of content popularity and spatial dependencies of data, on how the network operates and scales. As ICNs attempt to build a holistic approach to managing content on a shared network, many skeptical researchers deem its integration/replacement of the current Internet a mere impossibility [70].

In developing the TI, it is important to align with recent advancements in ICN research, especially in models that advocate for encompassing ICN as an overlay architecture. The main advantage from a TI perspective would be the readily available association of resources on demand, to potential TI applications. As ICN models aim to maximize the experience of users based on their usage profiles, the TI architecture could build better prediction and compensation models based on information garnered from neighboring nodes.

VII. NEW FRONTIERS FOR TI INTEGRATION AND SYNERGY

The potential applications of the Tactile Internet are indeed ever-expanding. In realizing its potential and impact, the TI could build on recent advances in tangent domains, aiming at expediting its development and expanding its scope. In the remainder of this paper we discuss our suggestions for some prime areas of expansion. This discussion is aimed at guiding current and incoming researchers in the TI area towards domains of prominent gain.

A. Massive M2M and IoT Communication: Out-of-Band TI Support

There are new developments in massive M2M, D2D and IoT communication that could drive more socially beneficial use cases and scenarios. For example, recent developments in nano networks could drive communication between sensors, actuators, and other devices at the tactile edge on a much finer level of granularity.

While TI control and operation may often require URLLC, there is significant room for developing assistive services that build on the abundance and scalability of massive M2M and IoT communication. That is, the question becomes how we can support TI operation by establishing parallel data streams that pool resources from the M2M/IoT communication spectrum. Such data could aid granular understanding of remote environments, without burdening E2E TI communication with non-URLLC traffic.

We envision this integration and synergy as a form of out-of-band E2E TI communication, thereby establishing a parallel E2E stream from one tactile edge to the other, feeding information to both the operator and the remote site of operation. Evidently, this would require IoT systems to leverage nearby computing and communication resources to achieve comparable E2E communication, and this is where assistive fog/cloudlet technologies could interplay. Recent work on expediting service delay in the IoT systems via fog architecture [71] could be a primer study in that direction.

B. Edge Computing Impact on Tactile Cognizance

While the TI architecture being developed is designed to be self-contained, there is significant room for edge computing support to expedite bootstrapping and error-recovery processes. That is, as TI components attempt to establish E2E communication, the TI architecture is designed to solicit and recruit the resources needed to meet the operational and communication mandates of the pertinent TI application. However, at many phases of this bootstrapping process (from E2E), there will be significant overhead in determining optimal paths and available resources, not to mention the gauging of reliability and constant oversight of QoS measures to ensure the delivery of stable communication from one tactile edge to another.

One of the major opportunities in development of TI bootstrapping, would be to couple its building phases with hierarchical cloud architectures that aim to exploit as well as optimize offloading across all the tiers of cloud services (i.e., mist–fog–cloudlet–cloud). Hierarchical fog computing has already been explored in multiple research endeavors, such as in [73], and we have presented a taxonomy of its tiers and interactions in [34].

This communication and coordination chain from end devices to the edge and from edge to the central cloud and *vice versa*, is already being optimized across a spectrum of performance metrics. Thus, developments in this realm will be of immense support to TI operation and resilience.

C. Role of Machine Learning in TI Operation

The use of data analytics and machine learning techniques surpasses the sheer enrichment of remote tactile interactions. As we strive to bridge the inevitable delay in communication, even in URLLC mode, there will always be a lag due to propagation delay over the projected long distances of communication. Thus, it is evident that path prediction and action classification algorithms would play a vital role in reducing the perceived delay in remote TI interactions.

However, the role of AI in general surpasses that level of interaction. As we develop the architecture for the TI, we are faced with significant challenges in recruiting and ensuring URLLC communication, especially over communication links that are inherently subjected to multi-E2E paths that could manifest unexpected/uncontrolled congestion.

In striving to predict the reliability and resilience of communication links, especially for time-critical TI applications, it is important to investigate historical as well as imperative data on each communication link. This will aid in provisioning interacting devices on the E2E path between TI edges, to ensure that a predetermined reliability threshold is met. AI could significantly aid in classifying and flagging links that are more likely to contribute to a failure in communication, or simply higher data error rates than allowed in connection setup.

Moreover, human interactions with TI devices, while mainstream, are not the sole type being considered. The TI architecture is also built to span machine-to-machine TI operation, and should thereby capture the majority of agility and adaptiveness traits currently exhibited by human operators. AI is expected to play a vital role in capturing intended reactions from current and past users of a given TI system, and aiding its machine counterpart in replicating its actions and potentially extrapolating on them when the need arises. This feeds into both scenarios where the TI edge is supposed to compensate for intermittent/poor connectivity, and when the machine-based TI edge is expected to carry forward its operation in complete autonomy.

D. User Mobility and Transparent TI Migration

TI operators should not be restricted to a static operational environment simply because of the URLLC mandate often expected in TI communication. There is a significant body of knowledge being developed on the transparent and autonomous management of service migration [74]. While the issue of mobility management on its own presents significant challenges [75], newer models are emerging in 5G networks to enable and improve mobility and session management via network slicing techniques [76].

In building on recent progress in network slicing, NFV and AI techniques, we could aim to develop the ability to profile and predict user mobility patterns, which will yield an uninterruptable seamless service migration in TI operation. While this is yet to be explored from a feasibility perspective, especially when machines are involved (potentially exclusively) on either ends of the TI communication, we envision TI interactions that not only support mobility of operators, tactile edge devices and network components, but also a predictable and computable model for TI mobility to reassociate with less-congested access points to the larger TI sphere, expanding on the notion of seamless TI mobility targeting congestion relief and ensuring higher E2E URLLC management.

VIII. CONCLUSION

The domain of TI operation is projected to encompass a myriad of applications, agile network components, and ever-expanding tactile edge devices. This paper presented the premise of tactile cognizance as a measure of enriching TI operation at the edge, by leveraging nearby resources. The diversity and potential of developments in IoT, edge technologies, and cloud-variants are all enabling a more expandable and reliable operation for the TI. The classifications listed in this paper, highlighting the role of TI cognizance in improving the experience of operators and automating the interactions of TI machines, present a foundational block for future developments in this promising technology.

Our final discussion on new frontiers in TI development sheds some light on the premise of developing tangent solutions to aid TI proliferation and expedites its manifestation in critical sectors. While the TI architecture is designed with URLLC at its core, the spectrum of use cases and potential gain from TI interactions mandate a broader outlook. That is, future developments in TI protocols and architectures should emphasize synergy with existing technologies to broaden the reach of the TI infrastructure, and further democratize the global set of skills that form its essence. ■

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