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5G-Enabled Education 4.0: Enabling Technologies, Challenges, and Solutions

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ABSTRACT New technologies such as mobile phones, social media and artificial intelligence, have significant impacts on every aspect of education, where digital connectivity is the foundation to support the way people learn. Current Internet and pre-5G cellular communication networks can deliver visual and auditory data, which enable distance/virtual learning. However, remote physical interaction between students and learning facilities, which is an essential part of a new education paradigm i.e., Education 4.0, is still missing. The 5G cellular network with excellent latency and reliability performance would be a game changer by enabling students to feel the physical objects and control them remotely. In this paper, we identify and discuss the unique opportunities the 5G networks can bring to Education 4.0, their technical challenges and potential solutions. We also showcase our Education 4.0 prototype of remote lab.

INDEX TERMS 5G verticals, education 4.0, remote control, AR/VR, remote lab.

I. INTRODUCTION

Recent technological advancements have transformed societies and improved standards of living globally. Mobile and digital connectivity are key drivers of this change, enabling several vertical industries including the imminent industrial revolution, i.e. Industry 4.0 [1]. Education 4.0 is a new paradigm in teaching and learning area which aims to prepare students and new generation of learners for upcoming industrial revolution [2] which requires new skills and includes new technologies such as advanced robotics, Industrial Internet of Things (IIoT), 3D printing, etc. The Covid-19 pandemic has also accelerated the transition from traditional education towards ubiquitous, personalised education that is part of the connected digital ecosystem. Traditional education relies on face-to-face teaching in classrooms with hard copy materials. All assessments and examinations are paper based with space and time limited laboratory sessions. Mobile and digital connectivity will revolutionize education and make knowledge easily accessible. For example, vast amount of learning materials such as video lectures, audio books, and lecture notes are extensively available almost at any time. It is also very easy to reach any kind of information in very small amount of time. Instead of paper based assessment, computer-based examinations can provide students instant results and feedback. Education 4.0 facilities include but not limited to AI assisted self-regulated learning with help of smart sensors and wearable devices [3], AR/VR aided remote learning facilities to enhance telepresence and remote learning experience [4], AI-based assessment and early progress recognition systems to allow students to learn on their own pace and to support students' success [5], smart campus facilities to provide flexible and immersive learning environment which include hosting online classes in different locations with help of holographic projections and AR/VR headsets, smart monitoring facilities for better space utilization [6] and remotely controllable robotic-aided learning facilities to realize *education at anywhere at any time* motto of Education 4.0 paradigm. Furthermore, the Covid-19 pandemic has made the adoption of online learning inevitable with 1.5 billion learners in 185 countries [7].

Unfortunately, there are several aspects of higher education that require physical interaction between the student and laboratory facilities. This makes remote access to physical

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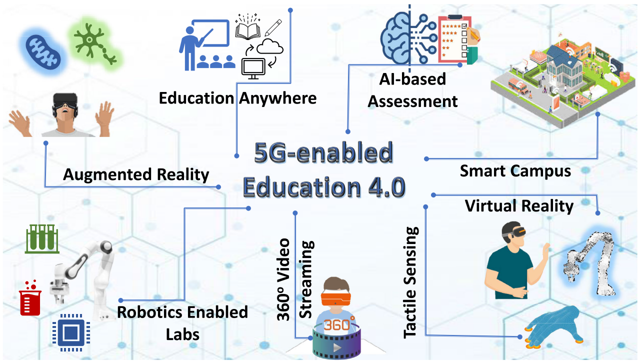

FIGURE 1. 5G-enabled education 4.0 environment.

laboratory one of the vital requirements of future education. The main impediment of remote access and control is the limitations of current communication networks that are widely available. In order to enable remote access to the physical laboratories, the communication network needs to be able to deliver sensory data, so students would be able to feel the texture or force or weight of physical objects in the labs. To have the real time physical interaction between students and physical objects including robots in labs, the communication network needs to be able to deliver control data with very high communication performance in terms of latency, reliability, and data rates.

The fifth generation of cellular communications (5G) will enable new opportunities for future education, which is known as Education 4.0 (see Fig. 1). 5G has outstanding performance and capability which are the foundations to support emerging technologies in Education 4.0. For example, Ultra-Reliable Low-Latency Communications (URLLC) would be the game changer since it enables the exchange of physical skills over the mobile communications. Enhanced Mobile Broadband (eMBB) supported Virtual Reality (VR) and 360° video streaming would provide immersive experience to students in virtual classes. Massive Machine Type Communications (mMTC) supported smart campus would allow students to check the availability of facilities such as classrooms, laboratories, and sport equipment and provide remote booking and scheduling services.

In this perspective study, we provide our vision on how 5G will become one of the most important enablers of this paradigm shift in education. Considering this broad vision, our study concentrates on remote learning on higher education, especially remote laboratory and training case. We examine key technologies that are vital for remote laboratory and training vis-a-vis use cases and 5G enablers. We, then identified the current challenges, enabling technologies by emphasizing 5G KPIs, as well as possible solutions on this context, where we highlight their uniqueness and difference from other verticals, such as Industry 4.0 and Healthcare. Finally, we demonstrate the case study of our remote laboratory prototype in Glasgow, UK and discuss future directions.

II. KEY ENABLING TECHNOLOGIES IN EDUCATION 4.0

In education, especially in higher education, institutions provide vast amount of digital resources, tools, and facilities which are mainly accessible via smart devices. However, the amount of data that needs to be processed and exchanged is rapidly increasing, with global mobile traffic expected to reach 607 exabytes (EB) per month by 2025 [8]. Unfortunately, pre-5G mobile communication systems have serious limitations in terms of data rate, latency, and reliability to enable new education environment.

In this section, we provide key enabling technologies, communication requirements, and example use cases of Education 4.0 by emphasizing the necessity of 5G mobile communications. Table 1 summarizes technological elements of Education 4.0, example use cases, corresponding 5G Key Performance Indicators (KPIs), and enabler 5G services. In addition, Table 1 provides the structure of the study in terms of how 5G contributes to Education 4.0 in technical perspective considering Education 4.0 use cases.

A. HIGH QUALITY 360° VIDEO STREAMING

Learners need to experience the remote environment as close to real physical attendance as possible to be fully satisfied from the learning experience. This is only possible with high quality 360° video streaming which will be observed via headsets to provide real-time experience of remote environment, irrespective of distance. For example, to achieve optimum user experience, we need to consider human eye as a reference. The human eye has the capability of focusing close and far objects, sees under low and high light, and has very wide view even without moving the head (horizontally 150° and vertically 120°) which requires 720 million pixels of display [9]. That is why the high resolution 360° video streaming is one of the essential requirements of future education to enable human eye-quality streaming in turn real attendance experience to remote environment. However, this requires very high date rates and ultra low latency, which will be delivered by 5G communications.

B. AUGMENTED REALITY (AR), VIRTUAL REALITY (VR), AND EXTENDED REALITY (XR)

The new education paradigm requires remote interactivity to achieve necessary level of learner experience. Remote lectures via video conferencing tools only are not enough to support the Education 4.0 vision where learners would be able to hear, see, feel and contribute in the remote learning environment. This will encourage students to actively participate in the learning process rather than being passive attendees. AR, VR, and XR will be the key enabling technologies of aforementioned interactive learning environment. AR mainly focuses on real environment by applying virtual information on top of it, while VR focuses on virtual environment without reality aspect which creates fully synthetic environment. On the other hand, XR is considered as integrated cyber-physical environment which becomes indistinguishable

TABLE 1. Education 4.0 requirements and 5G as an enabler.

Education 4.0 Requirements	Example Use Cases	KPIs	Enablers
Mobile Connectivity	Education at anytime, anywhere	Data rate, Availability, e2e Latency	eMBB, mMTC, URLLC
Game-based Learning	AR,VR and XR, Holograms	Data rate, e2e Latency	eMBB, URLLC
Personalized learning	On-the-fly AI/ML-based learning	e2e Latency, Data rate	eMBB, mMTC
E-assessment	AI-enabled tutoring and assessment	Data rate, Availability	eMBB, mMTC
Advice and Support	Intelligent Teletutor, Chatbot	e2e Latency	eMBB, URLLC
Learning Analytics	AI/ML-based future performance prediction(on-the-fly)	Data rate, Availability	eMBB

by user. AR, VR, and XR can provide common environments for learners who are physically in different locations for interactive and collaborative learning and will enable the *"education at any time and anywhere"* vision. Learners will be able to access, meet, communicate, and interact with remote cyber-physical environment. This will lead new learning methods such as hands-on immersive experience in remote labs via AR or examining microscopic plant cell as if it were human sized via VR. These will provide better understanding of subject, more motivation and better learner-tutor experience. The 5G mobile communication will play an enabler role because of stringent communication requirements such as low latency and high data rates as shown in Table 1.

C. TACTILE SENSING

Current capabilities of remote learning such as video and audio alone are not capable of providing the envisaged experience of Education 4.0. Students need to feel the environment to achieve full sense of presence. This new education paradigm provides real-time tactile sensing of remote environment to complete remote attendance puzzle which includes seeing, hearing, feeling, controlling, and communicating interactively. With recent advances in haptic communications, it is possible to feel texture of remote surface in real-time which provides real sense of presence. However, typical haptic sensors are sampled and transmitted with a frequency of more than 1kHz to ensure stability of the system [10]. In this sense, the system requires stringent latency, reliability and data rate requirements from the communication point of view which will be enabled with URLLC and eMBB features of 5G.

D. TELEOPERATION

Attending learning environment is not enough in Education 4.0. Students will have control over remote environment to achieve the interactivity which requires teleoperation capability with integration of robotics by real-time control as well as automation. Real-time remote control is one of the most important aspects of future education. It includes, but not limited to, remote access to laboratory environment and equipment for students to conduct real-time laboratory experiments with the aid of robots. This is an essential part of higher education, especially for science, technology, engineering, and mathematics (STEM) courses that require laboratory activities. However, advances in teleoperation come with stringent communication requirements to achieve seamless operation. Moreover, real-time control requires dedicated bandwidth, ultra-low latency as well as ultra-high reliability which cannot be supported by pre-5G communication technologies.

E. ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML)

Ubiquitous, flexible, adaptive, and personalized learning will be the core features of the Education 4.0. As discussed in [2], personalized and adaptive learning aims to provide education according to needs of individuals and adapt the curriculum accordingly. For example, higher difficulty tasks can be introduced to students when they reach certain learning milestones, allowing students to learn at their own pace. In addition, students can be assessed differently, and curriculum can be updated according to their needs which requires rapid exchange of huge data and high processing power where communication has the vital role. Furthermore, integration of AI and ML on communication networks via MEC also increases the overhead and the requirements of communications become more important. Therefore, pre-5G technologies becomes insufficient to support new education ecosystem.

The learning environment should also satisfy every single learner's needs which will require very flexible environment with high adaptability. New education environments will require on-the-fly AI and ML with minimal delay, which means that AI/ML algorithms will have to reside at the edge of the network. All previously described enabling technologies will rely on AI/ML to deliver high-quality user experience in Education 4.0. This puts stringent constraints on communication network, which in turn has to rely on AI/ML to self-optimise and support dynamic user demands. These communication needs include high data rates to enable fast exchange of huge amount of data, ultra-low latency to mitigate outdated data problem, and ultra-high reliability to ensure data integrity. Furthermore, wider coverage and ultra connectivity with other devices will further enable and develop future on-the-fly AI and ML.

III. TECHNICAL CHALLENGES AND 5G SOLUTIONS

The key technologies described in the previous section will provide new learning experiences of Education 4.0.

TABLE 2. Connectivity requirements of key enabling technologies with 5G vs 4G comparison [11]–[13].

Enabling Technology	Data Rate	Latency	Packet Loss Rate	5G	4G
Virtual Reality	> 530 Mbps	< 10 ms	$< 10^{-6}$	✓	X
Remote Interaction	100 - 200 Mbps	< 2 ms	$< 10^{-5}$	✓	X
High Quality 360° Video Streaming	> 120 Mbps	< 20 ms	$< 10^{-5}$	✓	X
Tactile Sensing	-	1 ms	10^{-6}	✓	X

However, in this new education environment, the number of smart devices and services will increase enormously, which will create challenges for mobile communication networks. In this section, we provide connectivity requirements of key enabling technologies in terms of mobile communications. In addition, we compare the 5G mobile communications with the 4G mobile communications to further emphasize the necessity of 5G as an enabler of Education 4.0. This has been summarised in Table 2.

A. DATA RATE AND CAPACITY

New education paradigm has very high data rate demands due to use cases that involve AR/VR/XR and 360° video streaming. Pre-5G cellular communication systems are incapable of supporting the high-data rate requirements of the Education 4.0 ecosystem, mainly due to limited spectrum. 5G New Radio (NR), on the other hand, will provide new spectrum opportunities especially in millimeter wave (mmWave) frequency bands (24 GHz to 100 GHz) [14]. mmWaves provide high data rates and larger bandwidth while the coverage is one of the concerns. Therefore, the 5G communications will make use different frequency bands for different use cases. For example, mMTC will use frequency bands below 1GHz which will provide wide area coverage in smart campuses. On the other hand, eMBB will make use of high frequency bands to provide higher data rates for specific applications such as live 360° video streaming. In addition, it is also possible to meet high data rate and capacity requirements with help of AI and ML driven digital twins. Digital twin (DT) is the digital representation of physical system by providing two-way or one-way communication between physical and digital system which makes possible to have real experience with lower requirements over digital model [15]. In remote laboratory and training case, it is quite convenient to deploy DT concept since the task is not life critical as in healthcare or surveillance for disaster management where guaranteed network performance is vital. For example, as shown in Fig. 2, DT can continue to operate with the help of integrated AI to mitigate mobile network limitations in case of poor network performance in remote laboratory experiment.

B. RELIABILITY AND LATENCY

Teleoperation, real-time remote control and tactile sensing require ultra-low latency and ultra-high reliability

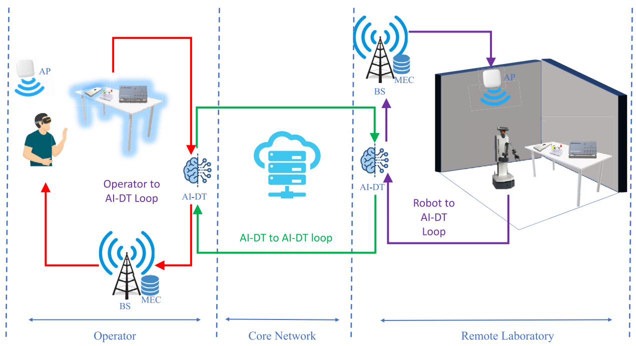

FIGURE 2. Remote laboratory with AI enabled digital twin (AI-DT) has three control loops. The operator to AI-DT and robot to AI-DT control loops provide instant interaction to the operator and the robot. The AI-DT to AI-DT control loop is to synchronize the two ends of the system and to mitigate poor communication in the core network.

(see Table 2) in mobile communications to enable seamless operation and high Quality of Experience (QoE). Less than 10 ms end-to-end latency and packet loss rate of below 10^{-5} are required to guarantee high quality and smooth remote operation [11], especially in mission critical scenarios. However, in remote laboratory and training use cases where the task is not mission critical, smooth remote operation can be achieved with AI/ML advanced mechanisms. AI aided Communication-Control Co-design (AI-CoCoCo) is one of the solutions to mobile network limitations by relaxing latency and reliability requirements based on dynamic requirements of control process [16]. In remotely controlled laboratory use case, some control packets may have outdated information or do not carry crucial information for the control task. Therefore, it is possible to relax latency and reliability requirements with AI-CoCoCo considering the value of each individual packet with respect to various communication and control related metrics such as latency, reliability, and Age of Information (AoI) instead of providing same resources to all packets.

C. EDGE/CLOUD COMPUTING

With new data-driven and AI-enabled education environment, mobile communications became more important to exchange huge amounts of data. However, the increasing number of connected smart devices and the resultant increase in the demand for bandwidth bring about new challenges for mobile communication systems. MEC [17] feature of the 5G mobile

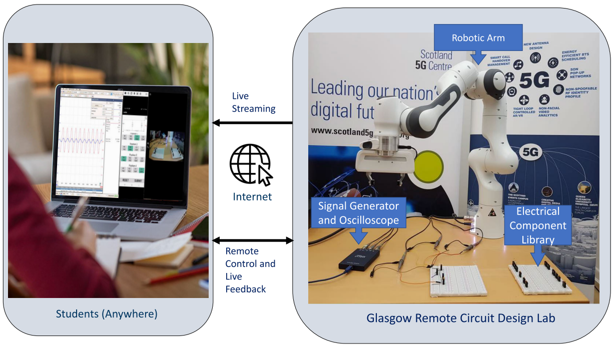

FIGURE 3. **The structure of the remote circuit design lab.**

communications provides cloud storage and computing capabilities available at the edge of the mobile network to enable data processing at proximity to the user. It enables exchange of inference instead of raw data which minimizes amount of data traffic, as well as isolates network data from core network to enable less resource consumption. For example, as shown in Fig. 2, MEC enabled remotely controlled laboratory can benefit from computing resources available on the edge of the network. Instead of transmitting raw sensory information from operator to controller over the communication network, MEC enables computation on operator side and transmission of control commands to the remote robot, which would dramatically decrease the use of communication resources.

D. SECURITY AND PRIVACY

The new education environment will have access to personal data that could also contain information on behaviours and skills of users which raises significant concerns on security and privacy. In addition, the increasing number of user devices towards a fully connected education ecosystem amplifies the consequences of security breaches. More secure authentication and encryption schemes are required to guarantee security and privacy in Education 4.0. Mutual authentication scheme is one of the solutions to this problem [18]. Both the user equipment and the network perform mutual authentication using Evolved Packet System Authentication and Key Agreement (EPC-AKA). AKA works based on symmetric-key authentication, which is more efficient than public-key based mechanisms. In remote laboratory and training, mutual authentication is vital to ensure the security of facilities as well as privacy of user. Both user and remote facility need to authenticate to assure that user is authorized to access the provided resources and resources are legitimate entity to access the information provided by the user. In addition, it is also important to assure that authenticated user continues to use the system after authentication process. Therefore, it becomes necessary to ensure perpetual authentication with the help of AI and ML where user can be certified continuously according to behaviour or previous user data.

IV. CASE STUDY: REMOTE CIRCUIT DESIGN LAB

In this section, we present one of the earliest prototypes of Education 4.0.[1] Remote circuit design laboratory prototype (see Fig. 3) offers an unrivaled experience of remote interaction to students all around the world. Physically, the lab is located at James Watt School of Engineering, University of Glasgow, UK. It is now accessible to students from all around the world where students take control of a robotic arm to conduct circuit design experiments remotely. The robotic arm is capable of assembling electrical circuits according to students' control commands by precisely placing electronic components (e.g. resistors, capacitors, etc.) on circuit boards. In addition, remote lab prototype enables remote measurement of real circuit to complete lab task in circuit design courses.

Specifically, remote lab enables three main capabilities. First, students can observe the remote lab environment via high quality video streaming, which provides more engagement to remote environment. Secondly, students can control the remote robotic arm using custom design control interface. Lastly, students are able to control lab equipment (digital signal generator and oscilloscope) to take remote measurements. To realize such an application, three main components are vital. First, high quality streaming to observe remote environment which requires video streaming software and hardware at both user and robot end. Secondly, robotic control is vital to control the remote robotic arm which requires control graphical user interface(GUI) at user end and control software at robot end. Lastly, control of laboratory equipment (e.g. digital signal generator and oscilloscope) is also important for remote experiment and measurement which requires hardware at laboratory and lab equipment GUI at user end. Presented prototype can be controlled remotely by using our custom GUI. From the GUI, students select components, e.g., capacitors, and resistors, to assemble electric circuit. After selection of components, control commands are transmitted to the remote robotic arm over UDP-based server. UDP-based server is used instead of TCP-based server to further mitigate overhead and in turn communication latency. Received control commands are executed by robotic arm to assemble the circuit. In addition, real-time video feedback can also be provided over different commercial video conferencing platforms such as Zoom and Microsoft Teams which allow multiple attendees on one laboratory session and create more interactive environment. In remote lab prototype, the 5G operating frequency is 3.75 GHz (i.e. it operates on band n78) with 100 MHz bandwidth. Experimental measurements our on 5G testbed are provided in Table 3. In addition to 5G-based tests, we have done experiments by inviting students from UK and China to use our prototype in which more than 200 students are attended and tested the remote lab. In these experiments, laboratory/robot end runs on 5G and student access the remote lab over conventional internet which supports equitable learning by enabling students

[1]The demonstration video: https://youtu.be/RCR5l72HVuM

TABLE 3. Throughput, latency, and jitter measurements on 5G.

Throughput (Mbps)						Latency (ms)			Jitter (ms)		
Uplink			Downlink								
Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
53	54.4	56	457	526.5	553	14	14.8	16	1	2.99	5.09

TABLE 4. Existing remote laboratory prototypes.

Study	Key Enabling Technologies				
	High Quality 360^o Video Streaming	AR/VR/XR	Tactile Sensing	AI/ML	Remote Interaction (Teleoperation)
[19], [20], [21], [22], [23], [24], [25], [26]	X	X	X	X	✓
[27]	✓	✓	X	X	✓
[28]	X	X	X	✓	✓
[29]	X	✓	X	X	✓

to access remote labs even from the places that 5G is not available yet. URLLC is the most important enabler of this use case since reliable and low-latency communication is critical in such applications to ensure high quality of service. Therefore, this prototype is crucial to investigate current capabilities and further emphasize the necessity of 5G communications.

A. TEACHING AND LEARNING PERSPECTIVE

So far, more than 200 students in UK and China have used our remote lab prototype in their circuit design courses and the majority of the students are satisfied with the remote lab and interested in conducting more remote lab experiments. In addition, the remote lab prototype provides vast amount of advanced resources such as robot aided circuit design lab to more students with more flexible way which is not always possible because of space and time limitations in traditional lab environment. It also provides game based teaching with the help of advanced technology which in turn grasps more attention of students and enables more effective learning. A study on Generation Z [30] reveals that mobile application and device aided teaching has significant positive effects on students' learning experience based on test scores of students learning with and without mobile applications and devices. In addition, students find mobile application and mobile device aided learning more enjoyable than the traditional learning approaches.

B. DISCUSSION

The remote lab prototype is crucial in terms of two very important aspects. First, it is critical for collecting students' responses to real life remote laboratory experience. Second, it is vital for demonstrating the communication requirements of remote laboratory use case with real life testbed implementation to further emphasize the necessity of the 5G cellular communications. There are some existing remote laboratory prototypes in the literature. These studies are compared considering Education 4.0 key enabling technologies in Table 4. As seen from the comparison table, most of the studies only have remote interaction/control capability while only some of them has AR/VR/XR capability. On the other hand, AI/ML and tactile sensing capability are not common in existing remote laboratory prototypes which are some of the most important features of upcoming 5G enabled Education 4.0. In our remote experiments within UK and between UK-China, we have used conventional internet connection on student side and robot side runs on 5G. We recorded communication latency of between $50-300$ ms within UK and up to 2 seconds between UK and China. Latency values are not stable and change depending on location, internet speed, or other uncontrollable parameters in the public internet which makes latency the main contributing factor of low quality user experience. Students expect more smooth interaction with remote environment. In addition, high latency also affects the quality of experience of students which could lower interest and motivation in the subject. Another important aspect is the reliability of the communication network. Similar to other industrial robots, the robot is sensitive to packet losses which affect the control performance. For example, it can compensate for up to 20 consecutive packet drops then the control process becomes unstable [31]. This implies that packet loss rate is very crucial in ensuring stable control which cannot be guaranteed with current communication networks. These results show the current capabilities as well as exigency of 5G and beyond cellular communications. In addition, they show how crucial the 5G is for future education where AR/VR headsets with 360° video and seamless control capabilities can enhance the way of education.

Another important aspect of 5G enabled Education 4.0 is the deployment and management strategies of the network to ensure high quality of service. There would be two strategies for deployment and management of network. The first is private campus networks, where universities would have their own and operate private networks by themselves. We already have well-known examples such as University of Glasgow, University of Surrey, Shanghai University, University of Tennessee, and Coventry University. Second strategy would be public network which are owned by Mobile Network

Operators (MNOs) instead of education institutions. MNOs would deploy, own, and manage the network. They can also create campus networks by using network slicing to ensure high quality of service to support 5G enabled Education 4.0 use cases. On the other hand, one of the most important challenges of setting up the 5G facility is the unavailability of UEs/dongles considering from user perspective. Currently, most advanced 5G UEs available are smart phones and 5G dongle availability is quite limited which limits 5G access and related testbed implementations. However, this challenge is expected to be solved with rapid development on 5G hardware and prevalence of 5G. In our case study, we have used our 5G dongles, which we built in-house at the University of Glasgow.

V. CONCLUSION

Education 4.0 is the future of education system which will be enabled by a collection of emerging digital technologies. Future education will create ubiquitous, immersive, adaptive and personalized learning experience. 5G is the key enabler of this ecosystem by supporting stringent communication requirements as well as providing high quality of experience for both the learners and tutors. In this study, we provide our vision on Education 4.0 by emphasizing the crucial role of 5G as an enabler. We investigate key enabling technologies and use cases of Education 4.0, especially the remote laboratory and training use case. In addition, technical challenges of Education 4.0 are identified and potential 5G solutions are evaluated. Lastly, we present our remote circuit design laboratory prototype as a case study and discuss teaching and learning perspectives, and emphasize the necessity of 5G for Education 4.0. As a future work, we will extend the capability and accessibility of the remote lab based on advanced 5G and robotics platforms in University of Glasgow.

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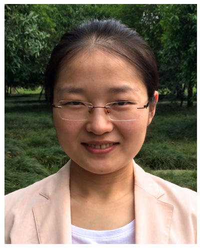

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