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Pre-6G Graduate Education of Communications Engineering

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As sixth-generation (6G) communications have been widely discussed in the past 2 years, it is now the right time to investigate the potential impacts of 6G communications on the current graduate education system of communications engineering. In this article, we articulate a set of existing problems with the graduation education of communications engineering and analyze the trends and challenges of pre-6G graduate education of communications engineering. By this article, we not only aim to diagnose the existing problems with corresponding trends and challenges but also to call for proactive measures coping with them. Besides, we would also like to use this article to encourage more and more brave undergraduates to participate in communications engineering, a fast-changing and far-reaching discipline.

Keywords: graduate education, pedagogy, communications engineering, 6G communications, telecommunications

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1 INTRODUCTION

Sixth-generation (6G) communications has been envisioned since late 2019 and already raised wide discussions in the communications science community (Letaief et al., 2019; Yang et al., 2019; Zhang et al., 2019; Dang et al., 2020; Saad et al., 2020). 6G communications is anticipated to bridge the physical space to the cyberspace (Nakamura, 2020), and the data services for augmented reality (AR) and virtual reality (VR) applications, demanding a tremendous amount of transmission capacity, will emerge in the 6G era (Lv et al., 2021). New conceptions and enabling information and communications technologies (ICTs) are being proposed and studied in order to realize this epic leap in communications in the 2030s (Dang et al., 2020). It is highly possible that 6G communications will reshape the telecommunications industry and will be quite different from currently launched fifth-generation (5G) communications in both technological and non-technological senses (Luo et al., 2020).

A futuristic research roadmap and scenario-specific design specifications will be adopted for prospective research activities, and 6G communications should be human-centric with a research emphasis placed on security, secrecy, and privacy as well as electromagnetic field (EMF)-awareness (Dang et al., 2020). This implies that the quality of experience (QoE) of wireless service subscribers, encompassing the health and psychological requirements, should be taken as the dominant performance measure of 6G communication systems (Kilkki, 2008). In addition, the human-centric nature of 6G communications also requires to balance the artificial intelligence (AI) based autonomy and human free will (Guo, 2020). To achieve the aforementioned goals of 6G communications, researchers have reached a preliminary consensus of emerging conceptions and enabling technologies for 6G communications:

- Artificial intelligence (AI)
- Decentralized network

- Reconfigurable intelligent surface (RIS)
- Terahertz and visible light communications
- Satellite-air-ground integrated network (SAGIN)
- EMF-aware transmission technologies

To prepare for the emerging trends and challenges of 6G, future researchers and engineers are expected to be equipped with different competence and mindset. Accordingly, this expectation requires to adjust and update the graduate education of communications engineering in the pre-6G era. We herein discuss the pedagogical issues of graduate education of communications engineering and provide some thoughts of the new pedagogical trends and challenges brought by 6G communications. Note that, the concept of *graduate education* discussed in this article mainly refers to doctoral education but is also related to master education involving cutting-edge research.

2 GRADUATE EDUCATION

2.1 Purposes of Graduate Education

To evaluate the potential effects of 6G communications on graduate education of communications engineering, we first would like to clarify the general purposes of graduate education applicable to any subjects, which are often misunderstood by both educators and graduate students.

The ultimate mission of education in any form is to equip graduate students with the potential to achieve something more significant by themselves and become the persons who they would like to be in the future. Abiding this ultimate mission, the purposes of graduate education should not focus on imparting specialized knowledge but leverage specialized knowledge as carriers to help graduate students attain *ability* and *independence*.

The ability refers to the talent, skill, and proficiency in both academic and daily areas. Once encountering a complicated problem, one with the ability will have the gamesmanship in mind to analyze the problem, search for proper information for reference, design a path to solve it, and, more importantly, take action. The independence for an individual mainly refers to the mental state and personality and is the mainstay of ground-breaking innovation. Independence will also enable an individual to fully wield his/her ability to overcome the challenge in life with self-awareness and free will.

Accordingly, the objectives of graduation education are to.

- Help graduate students exploit their potentials and recognize themselves.
- Help graduate students acquire a full picture of the state of the art in their studied subjects.
- Help graduate students gain adequate theoretical and practical abilities to explore and solve research problems.
- Help graduate students push the knowledge boundary of mankind forward.

2.2 Two-Phase Graduate Education

At most universities and research institutes over the globe, similar two-phase graduate education programs are adopted for communications engineering for achieving the educational objectives. The first studying phase is more lecture- and coursework-centric, aiming at delivering advanced mathematical and subject-specific knowledge as well as research methodologies above the undergraduate education level.

The second studying phase serves as a capstone on the fragmented course modules in the first phase and focuses on research problems, normally comprised by determining research topics, carrying out literature reviews, conducting a series of research activities, and publishing research works. Generally, graduate supervisors/mentors would assist in identifying, assessing, and refining promising research topics through several individual or group tutorials. The research topics might be formed by serendipity, developed from *macroscopic keywords*, e.g., ‘5G+’, ‘6G’, ‘AI’, ‘SDN’, ‘smart city’, and ‘vertical industry’, or associated with the awarded scholarships/studentships of graduate students. For the rest of the second phase, supervisors/mentors ideally act more like onlooking counselors (neither fractious tyrants nor aggrieved babysitters), who provide unbiased suggestions and check the completion of milestones to ensure their supervised graduate students on the right track.

3 FULL PICTURE OF COMMUNICATIONS ENGINEERING

Before discussing the impacts of 6G communications on graduate education, we must understand the roles of different sectors along the value chain of telecommunications. For this purpose, we provide a full picture of communications engineering in the sequel.

According to the classic definition of the purpose of communications by Claude E. Shannon (the founder of modern communications) (Shannon, 1948): “The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point,” we can summarize a generic modern communications system in **Figure 1**, containing almost all research objects in communications engineering.

Research activities in communications engineering are devoted to both theoretical and technical areas. The former is related to interpret, model, analyze, and optimize the included elements in **Figure 1**, while the latter targets technically sound prototypes and investigates how a theoretical conception can be realized as a prototype by hardware and software (Wang et al., 2019).

After both of the theoretical and technical research, non-technical factors will play a pivotal role to impact on whether a technically sound prototype has the potential to become a commercial success (Dohler et al., 2008). For clarity, we illustrate the complete value chain from a basic idea to an applied telecommunications product for end users in **Figure 2**. This value chain also manifests the partnership and the full spectrum of all sectors.

From **Figure 2**, the stakeholders of communications engineering include academic researchers, R&D developers and engineers with

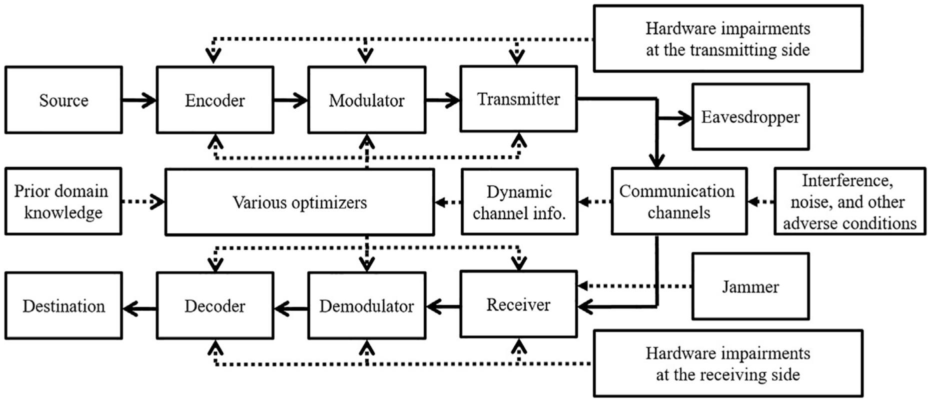

FIGURE 1 | Schematic diagram of a generic modern communications system.

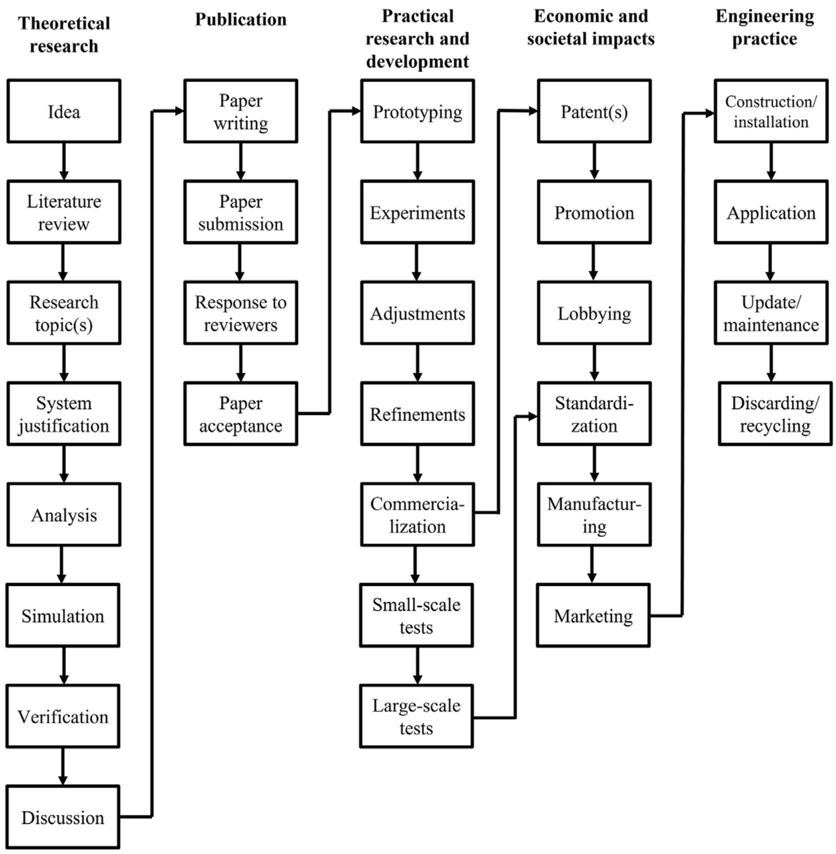

FIGURE 2 | Complete value chain from a basic idea to an applied telecommunications product for end users.

various vertical industries, equipment manufacturers and integrators, legal practitioner, standardization organizations, policy making organizations, telecommunications operators, communications service and content providers, advertisers, and end users (Maillé and Tuffin, 2014). Note that, it is end users who will finally determine whether the original idea really works and can make profits.

All researchers of communications engineering should always keep in mind that communications engineering, even though called communications science sometimes, is different from basic sciences, and the only goal of communications engineering research is to make information transmission in a more efficient and safer manner. Therefore, although tentative technological innovations either in theory or in practice should always be encouraged, purely theoretical research of communications engineering that cannot reach the end users and make a difference is a *de facto* failed attempt. Accordingly, the ultimate, essential, and unchanged touchstone of the usefulness of a communications technology is the marketing acceptance. Therefore, demands, costs, market discipline, and various human factors should never ever be omitted in the pre-6G era when pursuing the technological perfection of communications engineering by research. These factors are also yielding increasingly profound impacts on the graduate education of communications engineering.

4 EXISTING PROBLEMS, TRENDS, AND CHALLENGES OF PRE-6G GRADUATE EDUCATION

With all the existing graduate education system and the full picture of communications engineering as well as the basic requirements on qualified graduates in mind, we can now diagnose a number of existing problems and articulate the corresponding trends and challenges for the graduate education of communications engineering in the pre-6G era. Details are given in the following subsections.

4.1 Misunderstanding of Graduate Education

First and foremost, some graduate students might misunderstand the purpose of graduate education and simply take it as an extension of undergraduate education. A graduate school is neither a haven of unemployment that makes up one's missteps in the undergraduate study period nor a vocational training center teaching specific skills and knowledge. All pedagogical activities of graduate education aim to equip students with the ability and independence to overcome research challenges.

Without the correct understanding of graduate education in mind, graduate students might exhibit a lack of motivation and the sense of loss. Also, what they finally achieve from graduate education might also not be what they expected at the very beginning. For example, some believe that having a graduate degree can help with employability and the increase in earnings, which might not be true for most jobs irrelevant to research. Even if this is true, investing several years to obtain a graduate degree solely for enhancing employability would result in a high opportunity cost.

Regarding graduate education as an extension of undergraduate education would also lead to graduate students' underperformance in study and research. In most cases, the existing body of knowledge in the undergraduate study serves as regimented guidance for students to learn, but this is not the case in the graduate study. Graduate students might not expect such an answer from their supervisors/mentors but need to deeply dive down to the ocean of knowledge to find out the answer on their own, not to mention that the answer might not necessarily exist. All these make the difference between undergraduate and graduate education and are the very attraction for those looking for challenges and opportunities.

4.2 Independent and Critical Thinking Ability

Independent and critical thinking ability becomes unprecedentedly crucial in graduate education. Graduate students play much more important roles throughout the entire graduate educational procedure, from selecting research topics to structuring their theses. This is not only the requirement of the essential pedagogical purposes of ability and independence, but also due to the fast-paced research development in communications engineering. Candidly speaking, not strictly tracking the literature for a couple of months can make even the knowledge background of supervisors/mentors regarding certain specific research directions lagging behind. Thus, supervisors and mentors take more guidance and oversight responsibility in the pre-6G era, whereas graduate students need to rely more on their own independent and critical thinking ability when encountering specific research challenges.

In the meantime, critical thinking has a major effect on the appraisals of the all-round potentials of promising 6G technologies and is indispensable for graduate students to circumvent hypes.

4.3 Mathematics

The mathematical ability has become the core competency and the key to success in one's graduate studies. This is because the advancement of communications engineering, especially theoretical research, is highly restricted by the limited mathematical advancement, which results in a large number of intractable analytical and optimization problems (Dohler et al., 2011).

Several mathematical branches that were believed far from communications engineering 20 years ago have now been widely applied in this field, for example, game theory, two- and three-dimensional stochastic geometry, random matrix theory, percolation theory, machine learning theory, and artificial neural computing. Meanwhile, as communications networks are gradually becoming a part of the basic infrastructure and shall be with extremely high levels of resilience and reliability, reliability theory has already been introduced from power system engineering to evaluate the reliability of modern communication networks. Considering the research trends incorporating feasibility studies and marketing factors, a number of mathematical theories and methodologies usually applied in socio-economic disciplines are expected to be introduced to communications engineering in the near future, e.g., contract theory, value analysis, and prospect theory.

Accordingly, both educators and graduate students of communications engineering need to update their research toolbox and have more powerful mathematical tools.

4.4 Imbalance Between Theory and Practice

Meanwhile, the imbalance between theoretical and technical/practical research should be taken seriously (Gelonch-Bosch et al., 2017). Thanks to various simulation platforms widely applied nowadays, more and more graduate students do not need to get their hand dirty for studying communications engineering. Although we should never underestimate the importance of theoretical research in communications engineering, the excessive emphasis placed on theoretical research might undermine the engineering nature of this discipline and helps little to achieve the pedagogical purposes of ability and independence. In light of this, the theoretical, computer programming, and practical expertise need to be unified for the graduate education of communications engineering in the pre-6G era.

Moreover, the research routine based on numerical simulations by computers might not work well for the latest research of 6G communications (Raghavan and Li, 2019). This is because many physical phenomena related to 6G wireless technologies have not been fully understood and can hardly be modeled in an accurate manner, for example, the molecular absorption effect of terahertz radios, the non-Gaussian noise, and a variety of hardware impairments (Park et al., 2012; Guo et al., 2020; Ye et al., 2021). To consider real-world issues and propel practically feasible communications technologies forward, greater efforts need to be made on practical designs and hands-on experiments in the pre-6G era. To emulate and test communication systems and networks with complex structures on a massive scale, cloud computing technologies and the basics of using super computers/cloud workstations should be involved in the research and education of communications engineering in the pre-6G era. The corresponding programming languages, e.g., Python, C, and R, for carrying out complex computing tasks should also be explicitly included in the graduate curriculum of communications engineering.

It should also be ensured that all developed communications technologies are compliant with the latest telecommunications standards and security regulations (Lozano and Jindal, 2012). For this reason, widely applied telecommunication standards and protocols released by 3rd Generation Partnership Project (3GPP) and Institute of Electrical and Electronics Engineers (IEEE) would be introduced to graduates. More importantly, cooperative education involving industrial practices would become a must in the pre-6G era for having qualified graduates suited for both theoretical and technical innovation. Taking the EPSRC Centre for Doctoral Training in Communications (http://www.bristol.ac.uk/cdt-communications/), University of Bristol, as an example, long-term partnerships have been built with industry (both nationally and internationally), e.g., Bristol Research and Innovation Laboratory, Toshiba Europe. An industrial liaison office (http://www.bristol.ac.uk/engineering/ilo/) has also been formed to help the industry to engage with both students and academics at University of Bristol. There exist a number of ways that industrial partners can participate in the graduate curriculum design and reflect their demands on the graduates. For example, industrial partners are invited to be delegates in the External Advisory Boards, and experienced R&D researchers from industry can even become industrial mentors proposing and co-supervising graduates' research projects. There is a mature framework called the Industrial Mentoring Scheme at the departmental level to foster the industrial-academia partnerships at University of Bristol.

4.5 Interdisciplinary Studies Becomes Common

Enhancing interdisciplinary studies associated with communications engineering in graduate education is getting increasingly conspicuous. This trend requires graduate students to have a broader knowledge background, think out-of-the-box, and keep wider discussions with researchers in close disciplines. Needless to say, having the interdisciplinary mindset is one of the most efficient ways to trigger the spark of innovation. The recent ground-breaking developments of communications engineering for visible light communications (with photonics) (O'Brien et al., 2008), machine learning aided communications (with computer science) (Chen et al., 2019), RIS aided communications (with physics and materials science) (Basar, 2020), underwater communications (with marine science) (Shihada et al., 2020), tactile Internet (with cognitive science) (Aijaz et al., 2017), molecular communications (with molecular biology) (Guo et al., 2016), vehicular communications (with control science) (Shah et al., 2018), and 5G/5G + healthcare (with preventive healthcare) (Hossain et al., 2018) are the best proofs of this trend.

As with many new traits and interdisciplinary research directions, 6G communications will interact with various disciplines and vertical industries that have less or never been involved in the past generations. The development of ICTs in the 6G era will depend on talents not only from the area of communications engineering but also from many other areas. Therefore, a dual-supervision mechanism consisting of a primary supervisor with the communications engineering background and a secondary supervisor working on other relevant disciplines would be a potential solution conforming to the requirement of interdisciplinary studies.

4.6 Essential Skills

The essential skills in our context refer to the abilities that have direct impacts on the quality of one's research, for example, the proficiency in academic reading and writing, abilities to search, select, organize, and appraise state-of-the-art research works, vision and insight to predict the technological trends of communications engineering and find worthwhile research topics.

More effort and endeavor need to be dedicated to enhancing essential skills for the graduate education in the pre-6G era, which is now being underrated in the graduate education compared to those hard skills. In particular, LaTeX has undoubtedly become the most popular typesetting engine in recent years due to its powerful processing functionality for mathematical content and cross-reference, and should be grasped by graduate students at the beginning of their graduate studies.

4.7 Role Transition of Textbooks

Last but not least, we might admit that the canonical textbooks used for the graduate education of communications engineering have been published more than 10 years and are a bit old-fashioned, e.g., *Digital Communications* (Proakis and Salehi, 2008), *Wireless Communications: Principles and Practice* (Rappaport, 2002), *Wireless Communications* (Goldsmith and Firm, 2005), *Digital Communication over Fading Channels*

(Simon and Alouini, 2005), and *Fundamentals of Wireless Communication* (Tse and Viswanath, 2005). As communications engineering is undergoing much rapid and unremitting changes, which iterates by every generation, these canonical textbooks published 10 years ago might not reflect the latest trends, challenges, and requirements of communications studies, albeit quite helpful for understanding the rudiments.

However, because communications engineering is one of the fastest progressing disciplines since the 2000s, it is almost impossible to publish high-quality and comprehensive textbooks to capture its latest achievements in a real-time manner. For some latest research hotspots in communication engineering, e.g., RIS aided communications and SAGIN, it is even difficult to find an acknowledged monograph so far, let alone a systematic textbook. As a consequence, graduate students might hardly see the state of the art through textbooks.

Therefore, both educators and graduate students need to get used to the role transition of textbooks. The textbooks of communications engineering in the pre-6G era shall be used for the purpose of teaching methodologies rather than knowledge, while specific knowledge should be gained from reading recently published surveys, tutorials, and technical papers. Overall, canonical textbooks and selected references published recently are of equal importance for pre-6G graduate education, and neither should be treated as gospel.

5 CONCLUSION

In this article, we introduced the basic speculations of 6G communications, existing graduate education systems and the full picture for communications engineering, by which we can assess the potential impacts of 6G communications on the future graduate education of communications engineering. Graduate education is the lifeline of research, and the future research prosperity in the 6G era is to a large extent dependent on the talent pool of competent graduates. In this regard, we shared our thoughts on the graduate education of communications engineering in the pre-6G era and diagnosed the existing problems with corresponding trends and challenges. Even though we did not intend to provide the solutions to these focal problems in this article, we believe that proactive measures need to be taken at universities and research institutes to cope with them.

In addition, we would also like to demonstrate the challenging but attractive aspects of communications engineering in this article and thereby encourage more and more brave undergraduates who love explorations and challenges to participate in this fast-changing and far-reaching discipline.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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