IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received May 21, 2019, accepted June 24, 2019, date of publication June 28, 2019, date of current version July 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2925708

Basic Research Methodology in Wireless Communications: The First Course for Research-Based Graduate Students

ZHONGLI WANG[1], SHUPING DANG[2], (Member, IEEE), SINA SHAHAM[3], ZHENRONG ZHANG[4,5], (Member, IEEE), AND ZHIHAN LV[6], (Member, IEEE)

[1]College of Electrical and Information Engineering, Beihua University, Jilin 132013, China
[2]Computer, Electrical and Mathematical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
[3]Department of Engineering, The University of Sydney, Sydney NSW 2006, Australia
[4]School of Computer, Electronics and Information, Guangxi University, Nanning 530000, China
[5]Guangxi Key Laboratory of Multimedia Communications and Network Technology, Nanning 530004, China
[6]School of Data Science and Software Engineering, Qingdao University, Qingdao 266071, China

Corresponding author: Shuping Dang (shuping.dang@kaust.edu.sa)

This work was supported in part by the Provincial Key Scientific and Technological Research Projects of the Department of Science and Technology, Jilin, under 20170204021GX, in part by the National Natural Science Foundation of China under Grant 61661004, in part by the Guangxi Science Foundation under 2017GXNSFAA198227, and in part by the Shandong Provincial Natural Science Foundation under Grant ZR2017QF015.

ABSTRACT In this paper, we present an introductory course design for fresh research-based graduate students in wireless communications, which is planned to be delivered immediately after enrollment. The course aims at covering necessary research methodologies and the rudiments of wireless communications. Different from most graduate study curricula based on experiments, we design the course structure in an introductory manner by tailoring the course contents to a simplistic form and involving only simulations. We start by introducing the pedagogical background and our motivations for designing this course. Then, we present the fundamentals and the technological contents, followed by detailing the basic research methodology, strategies, and skills for deriving insightful analytical expressions and carrying out numerical simulations. We also verify the effectiveness of the course structure design by carrying out a teaching experiment and analyzing objective and subjective data collected from the experiment. By participating in this course, research-based graduate students are expected to gain a preliminary knowledge of the research methodology and strategies in the field of wireless communications as well as a research roadmap.

INDEX TERMS Wireless communications, research methodology, graduate students, telecommunications education, teaching experiment.

I. INTRODUCTION

Telecommunications stems from the electric telegraph invented by Morse in 1837. In 1897, Marconi's successful demonstration of wireless telegraphy made wireless communications come to public attention. The commencement of modern wireless communication research was triggered by the works published by Nyquist who found the maximum pulse rate for a given band-limited channel (a.k.a. the Nyquist rate) and the pulse shape maximizing the rate [1]. Later, a more important breakthrough in wireless communications was made by Shannon who creatively used statistics to construct the relation among transmit power, channel bandwidth, and channel capacity [2]. Shannon's work formally marked the 70-year long march of research in practical wireless communication systems, which gradually evolve from the first generation (1G) network to the fifth generation (5G) network.

The research and development associated with 5G networks are in full swing in recent years [3]. The '5G enthusiasm' reshapes the engineering education in wireless communications. In particular, recent years witnessed an increasing number of graduate students enrolled in the subject of wireless communication and related subjects [4]. On the other hand, with the enrollment expansion of graduate

The associate editor coordinating the review of this manuscript and approving it for publication was Ting Yang.

students, the knowledge backgrounds of different graduate students vary in a large scale. Today, it has become a common case that fresh research-based graduate students are not equipped with necessary research methodologies, especially for those whose first degree is not wireless communications or related subjects. The lack of a solid knowledge background and research methodologies make them difficult to carry out research in either an independent or a supervised manner. Therefore, our experience shows that it is helpful and even indispensable to deliver an introductory course for fresh research-based graduate students immediately after enrollment. In this way, students are able to grasp some fundamentals of research methodology and apply them to their research activities. To this end, we believe that such an introductory course should be well designed and prepared to deliver fundamentals and the basic research methodology in wireless communications to fresh research-based graduate students.

Although some teaching program designs for wireless communications are instructive and supporting, by going through the existing literature, we can hardly find an exact course design aiming at delivering the required rudiments for fresh research-based graduate students. A brief review of the relevant literature is presented as follows. In [5], a project-based instruction in wireless communications targeting undergraduate students equipped with preparatory mathematical knowledge at the junior level was presented, which serves as an early training in advanced topics for senior study. Teaching random signals and noise in communication systems was discussed through an experimental approach in [6]. Systematic curricula based on experiment assignments for wireless communications and mobile networking were detailed in [7]–[10], which are useful for students in senior and graduate levels with a solid knowledge background. Wi-Fi protocols that are mature and close to students' daily life were employed in the teaching activities of wireless communications in [11] due to their hands-on and easy-to-implement properties. Apart from experiment-based projects, simulation-based classroom instruction using MATLAB was given in [12], but only simplistic flat fading mechanism and outage probability were introduced without detailing the simulation setups and procedures. An extension of [12] to Nakagami fading scenarios was published in [13], but again simulation details are missing, which is thereby not suited for fresh graduate students without much research experience to read.

As reviewed, all above literature does not satisfy our goal for introducing fundamentals to fresh research-based graduate students who do not possess a solid knowledge basis of wireless communications. Some contents presented in these published papers a decade ago are outdated and do not match the fast-changing research activities today. This motivates us to propose our own course design aiming at delivering necessary research methodologies and the rudiments of wireless communications to fresh research-based graduate students who do not possess a solid knowledge basis. Considering the introductory nature of the course and the target student groups, we also tailor the course contents to a simplistic form and involve only simulations instead of physical experiment. The course can be delivered in the form of lecture series, special lectures, small-scale workshops, seminars, and individual tutorials.

In the rest of this paper, we first present the pedagogical background of this course design in Section II. Then, we give the fundamentals in wireless communications that should be covered in the 'first course' for usefulness and completeness in Section III. After these, to efficiently deliver the fundamentals, we present technological contents by several subtopics, including system modeling, analytical derivation, and numerical verification in Section IV. This course structure design consisting of fundamentals and technological contents covers a wide range of research topics and directions in academia and industry despite with simplified scenarios and contents. Based on the course structure design, we carried out a teaching experiment in the form of one-day seminar and present the data analysis in Section V. Two analytical methods, i.e., the comparative analysis by tests before and after delivering the seminar and course quality assessment are employed to verify the effectiveness of the course structure design. Finally, we summarize the paper and point out several future directions to improve the course structure design in Section VI.

The main textbooks recommended for reading in this course include [14]–[16], and the software required to be mastered through this course are MATLAB and Wolfram Mathematica. As a side contribution, we also provide a plenty of milestone papers beside the relevant contents in this paper, which can be viewed as guidelines for further study and research for students.

II. PEDAGOGICAL BACKGROUND

In this section, we provide the pedagogical background of the course design. It should be noted that the following background is mainly for the developing regions in the People's Republic of China, but can also be regarded as nationwide universal.

A. EXISTING ISSUES

As found by the Report of Admission Data Analysis of Chinese Master Students: 2015-2018 [4], recent years have witnessed a surge in the number of enrolled graduate students. On the one hand, it is positive that more and more students would like to participate in academic research and gain an in-depth knowledge of the subject. On the other hand, as a double-edged sword, graduate enrollment expansion has inevitably lowered down the admission baseline [17]. Internal admission investigations have shown that there is an increasing number of fresh graduate students who cannot even answer the basic questions that are regarded as must-know in the past. What is worse, the lack of knowledge associated with the basic research methodology and strategies has become a common issue in recent years. This has resulted in a significantly negative impact on the research performance of graduate students [18]. An increasing number of fresh research-based graduate students neither know how to carry out research at a graduate level, nor have a clear picture of the research roadmap. Undoubtedly, this situation has resulted in severe challenges in teaching organization design and researching at colleges and universities.

B. TARGET STUDENT GROUPS

Fresh research-based graduate students are the main target of this introductory course, as the course is dedicated to delivering fundamental research methodology and strategies. Other student groups that can benefit from this course are senior undergraduate students with little research experience, coursework-based graduate students, and on-the-job trainee students.

C. COURSE PREREQUISITES

There are three kinds of course prerequisites for the students participating in this course. First, students are expected to have adequate mathematical knowledge to understand the mathematical concepts and derivations presented in the course. This includes calculus, linear algebra, probability theory, and statistics. Second, students are expected to acquire fundamental knowledge of wireless communications and signal processing, so as to understand the basic concepts, e.g., modulation, coding, and detection, as well as randomness, causality, time-varying and time-invariant properties. Third, students are required to be equipped with programming knowledge for MATLAB and Wolfram Mathematica and be familiar with common operating commands. In case some students are not familiar with MATLAB and Wolfram Mathematica, a programming brief introducing MATLAB and Wolfram Mathematica is distributed to them for self-studying at the beginning stage of the course.

D. COURSE OBJECTIVE AND GOALS

Overall, the course objective is to equip fresh research-based graduate students with basic research methodology and research strategies in the field of wireless communications. In particular, this holistic course objective can be realized by the following goals:

- Understand what the objects of research are in wireless communications.
- Understand what the challenges would be in wireless communications.
- Grasp the basic research methodology in wireless communications.
- Understand the general research strategies in wireless communications and how to advance research activities.
- Understand performance analyses and optimization procedures in wireless communications.
- Master a series of mathematical and software tools that are useful in research but have not been covered in the undergraduate education.
- Understand the relation between analytical and numerical results and how to efficiently verify analyses by Monte Carlo simulations.

Overall, we aim to equip the fresh graduate students with the cognitive skills and abilities that they can find and promote their graduate-level research topics with critical and independent thinking, and appraise and judge research works via expertise and a set of principles and methods.

E. SIMULATION VS. EXPERIMENT

Undeniably, hands-on experiments are helpful for graduate students to understand how actually communication systems operate and master the approaches to design practical prototypes. However, experiment-based course designs in wireless communications also have apparent drawbacks. First, they require a much higher level of prerequisite knowledge and skills for students, which might not be directly associated with wireless communications *per se*, for example, transmission protocols, platform design, test, and debug that involve a set of sophisticated appliances. In addition, by involving physical experiments, the number of random factors that could affect the testing results goes much higher, and it is demanding to explore and explain the inherent mechanisms when results deviate from the theoretical expectation. As an introductory course, the course schedule is time-limited, which makes it more desirable if the essence of wireless communications relying on the random process can be manifested to students.

For this reason, we believe that hands-on experiments based on physical apparatus are more suited for graduate students who have already gained sufficient theoretical knowledge and dedicate to industrial designs. Besides, taking the course cost into account, simulation-based course designs are more cost-efficient and can be widely promoted without considering funding limit, as computer laboratories are ubiquitous at most universities nowadays. Hence, we choose to design the introductory course based on simulations relying on MATLAB and Wolfram Mathematica instead.

The reason for using MATLAB and Wolfram Mathematica is because of their universality and convenience in academia and industry. Also, both have already constructed a huge number of functions and simulators that can be easily used in wireless communications for performance analysis and system optimization [19]–[22]. To fully exploit the advantages of both computing platforms, we mainly use MATLAB for numerical simulations and Wolfram Mathematica for analytical derivations in this course.

III. FUNDAMENTALS

A. OBJECTS OF RESEARCH IN WIRELESS COMMUNICATIONS

Summarized from authoritative textbooks widely acknowledged in the communication community [14]–[16], the major purpose of wireless communications is to reproduce the information sent by the source(s) at the intended destination(s),

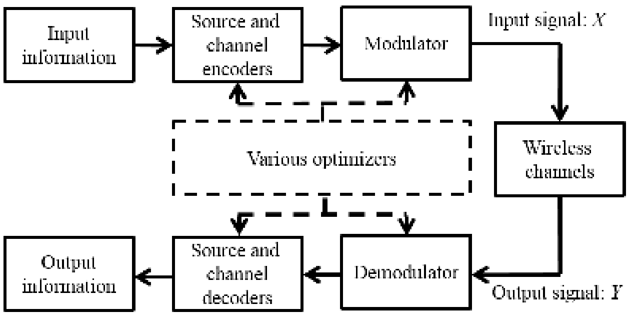


FIGURE 1. **A generic wireless communication system.**

which is transmitted over the wireless physical medium (i.e., the wireless channel) subject to a series of adverse mechanisms, including but not limited to path loss, shadowing, fading, interference, and noise. Therefore, we can briefly sketch a generic wireless communication system in Fig. 1. From the major purpose of wireless communications and the schematic in Fig. 1, we can easily identify the objects of research in wireless communications:

1) SOURCE

At the source, there are a series of topics worth investigating. First, in order to capture the information intended to be transmitted to the destination, we have to first quantify the information (e.g., voice, image, and text) in a comprehensible form for communication systems, which is normally a stream of bits with '0' and '1'. This procedure involves analog-to-digital (A/D) conversion. Furthermore, for data compression, secrecy enhancement, and/or reliability enhancement purposes, coding techniques can be introduced to map the original bit stream to a coded bit stream that might have a shorter or longer length. Then, we must modulate the bit stream to a symbol on a proper frequency band in order to efficiently transmit them. Therefore, for the source, researchers investigate how to incorporate proper techniques to transmit information efficiently and reliably. In this sense, adaptive coding and modulation schemes always attract researchers' attention [23]. In addition, hardware implementation at the source is also of high importance, e.g., antenna deployment and setup [24].

2) DESTINATION

Relative to the source, the research regarding the destination focuses on how to effectively and efficiently demodulate and decode the signal propagating over a wireless fading channel and contaminated by a variety of interference and noise. As a result, the optimal and adaptive receiver designs for different application scenarios are intriguing [25]. With the advance of adaptive receivers, interference and noise cancellation techniques at the destination have become attractive in recent decades [26]. Meanwhile, to provide appropriate quality of service (QoS), it is necessary to consider the synchronization and equalization issues at the destination, which are also frequent topics in research [27], [28].

3) WIRELESS CHANNELS

For wireless channels, there are four major research directions. First, how to get access to the channel states. Second, how to mathematically model the wireless channels. Third, how to improve the wireless channels so as to provide a mild environment for signal propagation. The first direction results in a plethora of research works dedicated to channel state estimation. The common approaches to estimate the channel states are to employ pilot signals and training sequences [29]–[31]. Having accurate channel state information (CSI) is the prerequisite to applying any adaptive mechanisms either at the source or at the destination and is thereby crucial [32], [33]. The second research direction provides the basis to simulate wireless communications and significantly facilitate the research activities of wireless communications. Furthermore, a proper mathematical model of the wireless channel also leads to an accurate channel prediction for taking proactive countermeasures. The last research direction tells us how to overcome or mitigate the disadvantages of wireless channels in a complicated electromagnetic environment. This direction is highly related to wireless network planning [34]. Most importantly, researchers are highly interested in the capacities of complicated wireless channels and devise a huge set of advanced mathematical tools to determine or approximate channel capacities [35]–[38].

4) IMPAIRMENTS

In practice, there are a large number of impairments preventing the information transmitted at the source from being correctly decoded at the destination. This happens particularly when signals are propagating over the complicated wireless electromagnetic environment. The most typical impairments include path loss, shadowing, various types of fading, distortion, mobility, interference, and noise, as well as channel estimation error and hardware imperfection. To transmit signals effectively and efficiently, researchers must first figure out the intrinsic principles and physical kernels of these impairments, take their adverse effects into account when modeling/analyzing wireless communication systems, and then propose corresponding countermeasures to neutralize or alleviate these impairments. One of the most efficient and reputable techniques to overcome these impairments is the diversity technique [39]–[44], which relies on multiple replicas of the original signal and transmits them through independently faded wireless channels. Therefore, as long as one signal replica can be received and correctly decoded, the intended information is successfully transmitted.

5) SECURITY AND SECRECY

As stressed in the major purpose of wireless communications, the information sent by the sources should only be received and decoded by the *intended* destination(s), which raises additional requirements of security and secrecy in wireless communications. Consequently, security and secrecy also fall within the realm of the research in wireless communications.

In the past, security and secrecy related issues were mainly considered in terms of information encryption based on number theory. In recent years, physical layer security exploiting the intrinsic randomness of the communication environment has been extensively studied [45]–[47]. Hence, the researchers have focused on how to transmit a signal in a specific way in terms of the instantaneous channel conditions to maximize the probability of correct detection at the intended destinations, while minimizing the probability of correct detection by eavesdroppers.

6) PERFORMANCE ANALYSIS

To analyze the pros and cons of wireless communication systems and evaluate their performance, there exist a variety of performance evaluation metrics, e.g., channel capacity, outage probability, average signal-to-noise ratio (SNR), error probability, spectral efficiency, energy efficiency, QoS, quality of experience (QoE), end-to-end delay, computational complexity, and user fairness. Calculations of the aforementioned performance evaluation metrics involve advanced and diverse mathematical tools. As a result, how to analyze the performance of wireless communication systems on an insightful and unbiased basis becomes crucial. In general, performance analysis should be application-driven and based on circumstances.

7) SYSTEM OPTIMIZATION

To deliver information in realistic networks, communication resources must be utilized, which include transmit powers, time slots, frequency bands, devices, and spaces. These communication resources need to be well organized and allocated to multiple entities in order to achieve a global optimum of the system. However, this is normally a nontrivial task, especially when multi-user and multi-cell architectures are considered [48]. First, the identification of key performance metrics as optimization objective function and constraints is not straightforward. Also, the formulated optimization problem couples several types of resources and can hardly produce a globally optimal solution in closed form. Researchers thus resort to a series of techniques to either simplify the formulated optimization problems or release certain constraints in order to find sub-optimal solutions [49]. Attention is also paid to heuristic searching algorithm designs in order to solve highly complicated optimization problems [50], [51].

B. GENERAL RESEARCH STRATEGIES IN WIRELESS COMMUNICATIONS

Regarding the objects of research in wireless communications summarized in the last subsection, from a practical perspective, there are three research strategies in wireless communications. We introduce them seriatim.

First, one can have a breakthrough in wireless communication research by proposing a novel communication paradigm/framework or a novel communication methodology that can be proved to be feasible in certain application scenarios and better than the existing techniques. Unmanned aerial vehicle (UAV) communications [52], multi-input and multi-output (MIMO) communications [53], cooperative communications [54], visible light communications (VLC) [55], and etc. are the successful examples of novel communication paradigms. Spatial modulation (SM) [56], non-orthogonal multiple access (NOMA) [57], space-time block coding (STBC) [58], and etc. are classic examples of novel communication methodologies. It should be noted that some breakthroughs are based on other existing paradigms or frameworks but with a significant difference from their original counterparts or introduce some considerable benefits. For example, SM can be regarded as the materialization of index modulation (IM) in MIMO architectures; NOMA can be viewed as a derivation of orthogonal frequency-division multiple access (OFDMA); UAV communications is a special case of mobile communications.

Besides, a summary or a proposal of a generic analytical methodology that can be used to solve a general kind of problems is also viewed as a milestone in wireless communication research, for examples, the moment-generating function (MGF) based and parameterization quantifying analytical frameworks proposed in [59] and [60].

Second, apart from breakthroughs, incremental advances are also of importance. Therefore, one might also pay attention to the improvement in existing communication techniques. For example, since the proposal of SM in [56], there have been a large number of enhanced, combined, and derivative modulation schemes following, e.g., space shift keying (SSK), generalized spatial modulation (GSM), Space-time block coded spatial modulation (STBC-SM), optical spatial modulation (OSM) [61]. These derivative schemes introduce new performance gains or trade-offs, which enrich the classic version of the technique and enable a wider application prospect.

Third, to promote a 'theoretically sound' prototype to a 'technically sound' system in practice, researchers must have a thorough understanding before standardization. Instead of proposing novel and incremental improved systems and methodologies, it is also meaningful to explore the inherent working principles as well as the applicability of existing wireless communication systems and methodologies. Again, taking the research activities associated with SM as examples, in-depth analyses of the performance of SM in terms of different performance metrics are provided in [62] and [63]. A variety of application scenarios of SM are provided in [64] and [65]. SM with different channel models and add-on techniques are studied in [66]–[68]. Practical issues and design guidelines regarding SM are demonstrated in [69]–[71]. All these works enhance researchers' understanding of SM and continuously promote this interesting concept to practice.

C. BASIC RESEARCH METHODOLOGY IN WIRELESS COMMUNICATIONS

As the research directions in wireless communication are multitudinous and varied over time, it is difficult or even

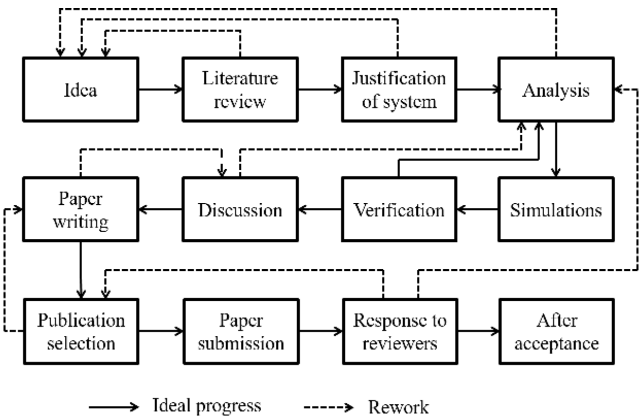


FIGURE 2. **Research progress from a basic idea to a published work.**

impossible to summarize a generic research methodology covering all topics. However, for most research activities in wireless communications, they share something in common. In this subsection, we summarize these similarities and expound the basic research methodology in wireless communications.

Before expounding the basic research methodology in wireless communications, we first illustrate the research progress from a basic idea to a published work in Fig. 2, which is applicable to most research activities in wireless communications. First, one should have a good idea, which could simply come from a fortunate stroke of serendipity or inspired by other similar ideas. Having a good idea is the first step in the research activity, but is normally nontrivial, which requires extensive reading and strong transferable ability. Once an idea is formed, an extensive and rigorous literature review must be carried out to check if this idea has been proposed by others. Then, two questions should be asked to oneself:

- If the idea has been proposed and investigated, is there anything else I can do to enhance the idea?
- If no relevant literature has found regarding the idea, why is such a good idea not attractive to the research community?

A proper literature review should be able to answer the aforementioned questions, by which one can conduct a technical justification of the system based on the idea. In the system justification, one should rethink his/her idea with more realistic conditions and constraints and double check whether it works. Subsequently, one has to analyze the proposed system based on his/her original idea in terms of one or multiple performance evaluation metrics. The analytical results need to be verified by numerical simulations in order to testify the correctness and usefulness. With both analytical and numerical results, one might gain a profound insight into the system through comprehensive discussions. After this stage, one comes to the paper writing and publication stages. As shown in Fig. 2, it is always possible to rework the previous stages in all stages and even overturn the original idea.

From the explanation of the research progress above, we summarize that the basic research methodology in wireless communications should consist of three key components: 1) justification; 2) analysis; 3) verification. These three components are interconnected and jointly enable a preliminary idea to a *theoretically sound* system. In the following paragraphs, we explain them seriatim.

First, to propose a wireless communication system or realize a technique, one must adopt a series of assumptions. Before doing anything else, one should consider whether the assumptions adopted in the scenario are appropriate. For example, access to perfect channel state information (CSI) is always assumed in order to simplify system modeling. However, This assumption is not always true in super dense networks where there exist massive nodes and fast fading environments, because channel estimation will yield very high signaling overheads in order to attain perfect CSI [21], [72]. Another example is the modeling of residual self-interference (RSI) in full-duplex communications, which is sometimes assumed to be negligible, sometimes a Rayleigh/Rician distributed random variable independent from transmit power, or a Rayleigh/Rician distributed random variable proportional to transmit power [20], [73]. These diverse models of RSI are only suited for certain cases, and one must wisely select the appropriate one when constructing his/her own system model [74]. System justification allows us to scrutinize all adopted assumptions in practical situations and ensure that we do not make impractical or contradictory assumptions [75].

Second, after justifying a system model, researchers then need to rigorously analyze the system via mathematical tools. The analysis of a system can be further classified into two categories. In the first category, researchers analyze one or more selected performance evaluation metrics by deriving their closed-form expressions, so that the inherent mathematical relations among the performance evaluation metrics and system parameters can be constructed and shown. In the second category, researchers can also perform analysis with respect to formulated performance optimization problems *per se*, so as to get access to the attributes and complexity of the formulated performance optimization problems. Such analysis paves the way for the proposal of an efficient solution.

Third, one does not know whether the analytical results are correct without numerical verification. The importance of numerical verification can be analogized by a simplistic six-sided dice throwing example. It can be easily derived that the probability of producing number six is $1/6$. To verify our analytical result, we can simulate the dice throwing procedure for a large number of times and count how many times we get number six so as to calculate the occurrence frequency. By checking how close the derived probability and the counted occurrence frequency are, we can verify the correctness of our original analytical result that the probability of producing number six is $1/6$. The above example shares the same nature as the numerical verification for analytical results in wireless communications.

As we mentioned before, the analysis of wireless communication systems can be classified into two categories. For the first category carrying out performance evaluation, one should compare the analytical and numerical results for the verification purposes. The numerical results are normally generated by numerical experiments based on repeated random sampling. Monte Carlo methods and MATLAB are jointly used to generate numerical results [76]. If the analytical and numerical results are close to each other, it is verified that the analytical results are correct under the current settings and can well capture the attributes of the system of interest. For the second category by analyzing the formulated performance optimization problems, researchers employ numerical experiments to generate the numerical performance metrics and compare them to the numerical results of at least two benchmarks. The first benchmark is a 'naïve' solution (e.g., random allocation and uniform allocation solutions) and the second benchmark is the optimal solution produced by brute-forth methods [77]. Ideally, the proposed solution is supposed to provide much better results than that of the 'naïve' solution and be comparable to the optimal solution. Meanwhile, the computational complexity or hardware/system requirements to yield the proposed solution are much lower than the optimal solution relying on brute-forth methods. In this way, the effectiveness and efficiency of the proposed solution corresponding to the formulated performance optimization problem can be verified.

Overall, the basic research methodology in wireless communications can be summarized as follows. One should first have a good idea and employ systematic methods to justify the feasibility of the system as well as the adopted assumptions. Then, mathematical tools shall be applied to rigorously analyze the system so as to quantify the relation among system performance and a set of system parameters and provide profound insight into the constructed system. Finally, numerical simulations are carried out to verify the analysis by mathematical tools. Once this basic research methodology is in use and the corresponding procedures are done, the constructed system based on the original idea and the corresponding analysis can be tentatively regarded as *technically sound*.

D. CHALLENGES OF RESEARCH IN WIRELESS COMMUNICATIONS

As we have introduced the research objects, general research strategies, and basic research methodology in wireless communications, we are now able to elaborate on the challenges of research in wireless communications. Again, we should focus on the research progress as shown in Fig. 2. Having an idea is the first step to carry out one's research. However, experienced researchers might all agree that this would be the most demanding step. This is because having a good idea requires a good sense of discernment, which can only be endowed by wide reading and in-depth knowledge of research frontiers. There are some general tips for fresh graduate students in wireless communications for having good ideas. First, it is suggested to have general understanding of the research hotspots and communication scenarios in recent years. Also, it is also suggested to know what bottlenecks are hindering the development of current wireless communication technologies. Relevant information can be obtained by tracing the workshops and tutorials given in IEEE International Conference on Communications (ICC) and IEEE Global Communications Conference (GLOBECOM) in the last few years. In addition, the 'call for papers' leaflets of several leading journals and magazines for wireless communications (e.g., IEEE Journal on Selected Areas in Communications, IEEE Transactions on Industrial Informatics, IEEE Communications Surveys & Tutorials, IEEE Communications Magazine, and IEEE Wireless Communications) are also very useful to get to know what researchers in academia and industry are concerned about.

Opposite to having no idea, having too many ideas without discernment and critical thinking is also an issue. This can be commonly found among fresh research-based graduate students. For this issue, some research management skills should get introduced, which requires knowledge at a senior level and is thereby not recommended to fresh graduates at early stages. Instead, regular seminars should be held to discuss these preliminary ideas and lead fresh students to master the ability to critically appraise an idea by reviewing the relevant literature and even constructing a small-scale and simplistic system for testing.

Meanwhile, once a research topic has been confirmed, carrying out a literature review in an efficient manner is also a challenge for most novice researchers. From our own experience, it is normally too difficult to understand technical works with a huge amount of mathematics for fresh graduate students. Therefore, we recommend reading tutorials, magazine articles, and introductory overviews first. Then, based on the reading of these introductory works, fresh graduate students might find more technical works to read. Also, these introductory works can help them to reorganize their research schedules and form a full picture of state-of-the-art techniques pertaining to their research topics. For the literature review, Google Scholar (https://scholar.google.com/) and IEEE Xplore (https://ieeexplore.ieee.org/) are in particular recommended to fresh graduate students. Besides, arXiv (https://arxiv.org/) is also a helpful database to trace the latest preprints released online.

After the literature review, the system justification becomes a challenge, especially for fresh research-based graduate students who do not have much experience. To be realistic, for most cases, standing on the shoulders of giants would not be a bad idea, and we suggest to check the proposed system model by comparing to existing system models, especially presented in those widely recognized papers and millstones. Then, if an assumption is widely adopted in most literature, one should reckon on the physical facts behind this assumption and inspect whether these physical facts still hold in his/her system model. If an adopted assumption has never been seen in the literature, more attention should be paid to explore whether such an assumption is valid, and the physical principles behind the assumption. In addition, thorough understanding of how systems actually operate in practice is also the key for constructing correct and accurate system models. In wireless communications, modeling a system requires knowledge of prevailing standards and protocols [75].

Having justified the system model, analysis becomes the next challenge. Again, we split the discussion for the two aforementioned categories of analysis. For works belonging to the first category by analyzing performance evaluation metrics, the common challenges include the selection of performance evaluation metrics and the mathematical derivations of closed-form expressions. The selection of performance evaluation metrics for analyzing should refer to the goal of the proposed system and the contexts. For example, to propose a certain high-reliability communication system, its reliability characterized by outage probability and error probability would be analyzed; to propose a certain low-latency communication system, the end-to-end delay should be taken as a crucial performance evaluation metric to analyze. If a trade-off between metric A and B is discussed in the proposed system, both metric A and B as well as their inherent relation shall be analyzed. However, for sophisticated wireless communications, it is generally difficult and even impossible to derive the closed-form expressions for the performance evaluation metrics.[1] General techniques for obtaining closed-form expressions and approximations are detailed in Section IV-C.

For works belonging to the second category dedicated to performance optimization, formulation of optimization problems is relatively easy, as long as a proper objective function can be defined and constraints are fully taken into consideration. In this regard, the challenge of analysis mainly refers to obtaining the solution to the formulated optimization problem. To obtain the solution, we first need to inspect the nature of the formulated optimization problem, in particular, its convexity/concavity. If a formulated optimization problem is convex/concave, we can easily solve it by using the method of Lagrange multipliers or the Karush-Kuhn-Tucker (KKT) conditions [79]. Sometimes, we can even derive a closed-form expression for the final solution [80]. For non-convex/non-concave optimization problems, complex optimization techniques are required. Some of them focus on transferring the original non-convex/non-concave optimization problem to an approximate optimization problem that is convex/concave by modifying the objective function or relaxing one or more constraints [81]. Some techniques convert the original non-convex/non-concave optimization problem to several sub-problems that are convex/concave. Then, solving these sub-problems will produce a sub-optimal solution that is comparable to the optimal solution [49]. Moreover, some artificial intelligence (AI) related techniques, e.g., machine learning and genetic algorithms, can also be applied to approach the optimal solution of a non-convex/non-concave optimization problem on an iterative basis [51], [82].

Last, but not least, challenges also exist in the simulation and verification stages. Simulating a wireless communication system is always not a trivial task. Simulation platform and algorithms for random sample generation must be skillfully chosen so as to achieve a good balance between simulation accuracy and computational complexity. Masterful programming and debugging are equally important for simulating wireless communication systems, especially when the numerical results produced by the simulation programs do not match the expectation. MATLAB is recommended to novice researchers for carrying out numerical simulations due to its accessibility and a large number of useful embedded toolboxes [19]. Note that, the embedded functions on MATLAB can only generate random variables abiding several basic distributions, e.g., Gaussian, exponential, Rayleigh, and Poisson distributions. To generate random samples following advanced random distributions, e.g., Rician, Nakagami, and Weibull distributions, one should combine random variables abiding basic distributions to form them [12], [13], [83], [84], which demands good understanding and technical expertise of the relations among different random distributions. To provide some clues for fresh graduate students, contents regarding generating random samples are presented in Section IV-D.

IV. TECHNOLOGICAL CONTENTS REQUIRED TO BE COVERED

Following the fundamentals introduced in Section III, we infuse them into the techonological contents presented in this section. Most contents presented in the course are clipped off and summarized from [14], [15], but with our own descriptions and interpretations, for the purposes of teaching demonstration.

A. SYSTEM MODELING OVER RAYLEIGH FADING CHANNEL

To have an in-depth investigation and understand the intrinsic nature of wireless communication systems, we must rely on mathematical tools to model a generic wireless communication system first. Simplifying Fig. 1, we can view a wireless communication system from the perspective of signal and system in either time or frequency domain. In general, taking the view of signal and system, a communication channel can be regarded as a system with input signal $x(t)/X(f)$ (in time and frequency domain) and output signal $y(t)/Y(f)$. The system is modeled as a linear time-variant filter, in which the channel impulse response $h(\tau; t)$ varies over time. Consider a

[1] The closed-form expression is a terminology for a kind of mathematical expressions that can be assessed in a finite number of operations and has a rigorous mathematical definition [78]. In general, a closed-form expression in the context of wireless communications should not include infinite sum, infinite product, infinite continued fraction, limit, derivative, and integral. However, special functions are normally acceptable as a part of closed-form expressions in the research community of wireless communications, e.g., the complete/incomplete gamma functions, Bessel function, exponential integral function, Q-function, Lambert W function, and their composites.

general form of modulated signals in the time domain:

$$x(t) = \text{Re}\left\{x_B(t)e^{j2\pi ft}\right\}, \tag{1}$$

where $x_B(t)$ is the equivalent baseband transmitted signal. It is widely accepted that there are multiple paths from the transmitter to the receiver because of reflection, scattering, and diffraction, by which the sent signal from the transmitter can reach the receiver. Hence, if we assume all paths are linear, the linear time-variant filter channel is characterized by the following input-output relation in the time domain:

$$y(t) = \sum_{n=1}^{N} a_n(t)x(t - \tau_n(t)), \tag{2}$$

where N is the number of paths; $\{a_n(t)\}$ and $\{\tau_n(t)\}$ represent the time-variant attenuation factors and delays corresponding to the nth path at time t. Substituting (1) into (2) yields

$$y(t) = \text{Re}\left\{\left(\sum_{n=1}^{N} a_n(t)x(t - \tau_n(t))e^{-j2\pi f\tau_n(t)}\right)e^{j2\pi ft}\right\}, \tag{3}$$

by which we can easily extract the equivalent baseband received signal to be

$$y_B(t) = \sum_{n=1}^{N} a_n(t)x(t - \tau_n(t))e^{-j2\pi f\tau_n(t)}. \tag{4}$$

By the rudiments of signal processing, we have $y_B(t) = h(\tau; t) \circledast x_B(t)$ ($\circledast$ denotes the convolution operation), which results in the explicit expression of the time-variant impulse response by $h(\tau; t) = \sum_{n=1}^{N} a_n(t)\delta(t - \tau_n(t))e^{-j2\pi f\tau_n(t)}$, where $\delta(\cdot)$ denotes the Dirac delta function.

Now, assuming $N \to \infty$, we can generalize (4) and express the input-output relation in baseband by integral as

$$y_B(t) = \int_{-\infty}^{\infty} a(\tau; t)x_B(t - \tau)e^{-j2\pi f\tau}\mathrm{d}\tau, \tag{5}$$

which gives the channel impulse response $h(\tau; t) = a(\tau; t)e^{j\theta}$, where $\theta = -2\pi f\tau$; $a(\tau; t)$ is called the amplitude variation (a.k.a. channel fading) in the received signal. The amplitude variation is unpredictable, but follows a certain random distribution, e.g., Rayleigh, Rician, Nakagami distributions, according to the central limit theorem; θ is called the phase variation that is assumed to be uniformly distributed over $[0, 2\pi)$ by the central limit theorem. Consequently, assuming the channel is frequency-flat and slowly faded and the received signal is polluted by a complex additive white Gaussian noise (AWGN) term $n(t)$ with average noise power N_0, the input-output relation in the baseband within a signaling interval can be given by

$$y_B(t) = ae^{j\theta}x_B(t) + n(t), \tag{6}$$

where the amplitude variation a is assumed to be a Rayleigh distributed random variable corresponding the Rayleigh fading channel model in this course design. The probability density function (PDF) and cumulative distribution function (CDF) of a are given as follows:

$$f_A(\epsilon) = (2\epsilon/\mu)e^{-\epsilon^2/\mu} \Leftrightarrow F_A(\epsilon) = 1 - e^{-\epsilon^2/\mu} \tag{7}$$

where μ is the average channel power gain.

B. CALCULATIONS OF PERFORMANCE EVALUATION METRICS

To appraise the performance of the above constructed communication system, one shall first choose proper performance evaluation metrics. In this course design, we adopt average SNR, outage probability, and error probability as performance evaluation metrics, because of their simplicity and universality. The average SNR can be regarded as the most common and best understood performance evaluation metric in wireless communications, which is directly associated with the received signal detection process and therefore an intuitive indicator of the system fidelity. Outage probability is defined as the probability that the system throughput follows below a preset outage threshold and is relatively easy to calculate once the random distribution of the instantaneous SNR is known. Error probability is defined as the probability that the originally transmitted signal from the transmitter is erroneously detected at the receiver and is much more complicated in terms of mathematical formalization due to the randomness of additive noise. However, error probability is the most revealing metric about the system nature and thus of primary interest for performance evaluation.

1) AVERAGE SIGNAL-TO-NOISE RATIO

By (6), it is straightforward to determine the instantaneous SNR by

$$\gamma(t) = a^2\mathbb{E}\{|x_B(t)|^2\}/N_0, \tag{8}$$

where $\mathbb{E}\{\cdot\}$ returns the expected value of the random variable enclosed. For constant-envelope modulation, e.g., M-ary phase-shift keying (M-PSK), we can simply denote $P_t = \mathbb{E}\{|x_B(t)|^2\}$ as the transmit power. Therefore, we can determine the average SNR by

$$\bar{\gamma} = \mathbb{E}\{\gamma(t)\} = \mathbb{E}\left\{a^2\right\}P_t/N_0 = \mu P_t/N_0. \tag{9}$$

2) OUTAGE PROBABILITY

Based on the instantaneous SNR defined in (8), we can define the outage probability with normalized bandwidth as

$$\begin{aligned} P_o(R_{\text{th}}) &= \mathbb{P}\left\{\log_2(1 + \gamma(t)) < R_{\text{th}}\right\} \\ &= \mathbb{P}\left\{a^2 < N_0(2^{R_{\text{th}}} - 1)/P_t\right\} \\ &= 1 - e^{-N_0(2^{R_{\text{th}}}-1)/(\mu P_t)}, \end{aligned} \tag{10}$$

where $\mathbb{P}\{\cdot\}$ denotes the probability of the random event enclosed and R_{th} is a preset rate threshold, below which the wireless communication system is in outage.

3) ERROR PROBABILITY

Considering a simplistic scenario where binary PSK (BPSK) and maximum likelihood (ML) estimation are adopted at the transmitter and receiver, the transmitted symbols for bits '1' and '0' can be denoted as $\chi_1 = \sqrt{P_t}$ and $\chi_0 = -\sqrt{P_t}$, respectively. Assuming the CSI represented by $ae^{j\theta}$ is perfectly known at the receiver, the ML estimation criterion is thereby given as

$$\hat{x}_B(t) = \arg\min_{\dot{x}\in\{\chi_1,\chi_0\}} \left\{ |y_B(t) - ae^{j\theta}\dot{x}| \right\}. \quad (11)$$

By the properties of the Gaussian distributed noise term $n(t)$, we can derive the conditional error probability conditioned on a as [14]

$$P_e(a) = \mathbb{P}\left\{\hat{x}_B(t) \neq x_B(t)|a\right\} = Q\left(\sqrt{2a^2P_t/N_0}\right), \quad (12)$$

where $Q(\cdot)$ is the Q-function (a.k.a. the tail distribution function of the standard normal distribution). The error probability can be determined by averaging $P_e(a)$ over a as follows:

$$P_e = \int_0^{\infty} P_e(a)f_A(a)\mathrm{d}a = \frac{1}{2}\left(1 - \sqrt{\frac{\mu P_t}{N_0 + \mu P_t}}\right). \quad (13)$$

The integral can be computed on Wolfram Mathematica by the code block infra

```
Qfunc[ϵ_] := Erfc[ϵ/Sqrt[2]]/2;
Integrate[Qfunc[Sqrt[(2 a^2 P_t)/N_0]] * ((2 a)/μ)
        Exp[−(a^2/μ)], {a, 0, Infinity},
        Assumptions → {P_t > 0, N_0 > 0, μ > 0}]
```

C. ANALYTICAL DERIVATIONS OF CLOSED-FORM EXPRESSIONS

If a certain performance evaluation metric of a system can be determined in closed form, the system is said to be mathematically *tractable* in terms of that performance. The examples given in the last subsection are simple and thereby all mathematically tractable. However, for complicated wireless communication systems in state-of-the-art literature, the analytical derivations of performance evaluation metrics are not straightforward and sometimes even impossible due to the limitations of mathematics. To facilitate research activities for fresh graduate students, it is necessary to introduce a series of general skills for deriving closed-form expressions in the course design.

First of all, to be efficient, we recommend referencing reputable formula booklets and tables [85]–[87]. Some web-based searching engine for formula would also be useful (e.g., https://dlmf.nist.gov/). One might also resort to the powerful functionality of Wolfram Mathematica and Maple for analytical derivations of closed-form expressions, e.g., the example following (13). In case no such a closed-form expression could be found in the aforementioned resources, we may consider

- Expand the original equation or integrand of an integral in a certain way and swap the operation order among several mathematical operations if allowed. Power series expansion, the multinomial theorem, and partial fraction decomposition are commonly used for this purpose.
- Expand the original equation or integrand of an integral in a certain way and discard the terms that have little impact on the entirety under certain conditions and obtain an approximate or asymptotic expression in closed form instead.
- Make some modest assumptions to idealize and further simplify the system so as to obtain a reduced form of the original equation.
- Employ widely applicable alternative forms/approximations/bounds of special functions that consist of simpler and ordinary functions.
- Employ the Fubini-Tonelli theorem to swap the order of several integration operations under certain conditions.
- Employ the Lebesgue's dominated convergence theorem to swap the order of integration and differentiation operations under certain conditions.
- Integrate by substitution to reduce the form of an integral.

D. VERIFICATION BY NUMERICAL SIMULATIONS

Having calculated the three performance evaluation metrics in closed-form expressions in Section IV-B, we now wonder whether these derived analytical expressions are correct. To achieve this goal, we employ numerical simulations based on Monte Carlo methods in the course design, and the corresponding simulations are called Monte Carlo simulations. Monte Carlo methods provide non-deterministic approaches that are capable of approaching analytical results by a large number of repeated random trials [88]. Theoretically, when the number of random trials N_S goes to infinity, the relative error between the numerical and analytical results will become infinitesimal if the analytical results are correct and exact. If the analytical results are approximate, there shall exist an acceptable relative error between the numerical and analytical results when $\mathsf{N}_S \to \infty$.

To implement Monte Carlo simulations successfully, there are four crucial steps. We elaborate on them as follows:

1) INITIALIZATION

Prior to carry out Monte Carlo simulations, we must define the deterministic procedures, stochastic process, and configure all parameters in an explicit way. The deterministic procedures mainly refer to the modulation, coding, transmission, reception, and estimation procedures. In our example, we employ an uncoded BPSK transmission scheme at the transmitter, and shall thereby represent bit '1' and '0' by symbols $x_B(t) = \sqrt{P_t} + j0$ and $x_B(t) = -\sqrt{P_t} + j0$ (only the in-phase component in the signal constellation plane is used due to the binary antipodal nature of BPSK), respectively. The value of transmit power P_t should also be assigned. Next, for the signal propagation procedure characterized by a stochastic process, we must define the distributions of random variables, e.g., a, θ, and $n(t)$ (c.f. (6)):

$$\begin{cases} a \sim \text{Rayleigh}(\mu/2) \\ \theta \sim U(0, 2\pi) \\ n(t) \sim \mathcal{CN}(0, N_0) \end{cases} \tag{14}$$

as well as the parameters μ and N_0. At the receiver, we implement the ML estimation scheme given in (11) with the defined signal space $\{\chi_1, \chi_0\} = \{\sqrt{P_t}, -\sqrt{P_t}\}$. Also, we assume that the incoming bit stream in the simulated wireless communication system is equiprobable, and hence the elements in the signal space $\{\chi_1, \chi_0\}$ will be equally chosen to transmit. Mathematically, we have

$$x_B(t) = \begin{cases} \chi_1, & \text{with 50\% chance} \\ \chi_0, & \text{with 50\% chance} \end{cases} \tag{15}$$

Most importantly, the number of random trials N_S should also be directly or indirectly defined in the initialization stage.[2] There exists a trade-off when setting N_S. On the one hand, to guarantee the statistical completeness and ergodicity of simulations, we should let N_S be sufficiently large. On the other hand, it is worth pondering a practical simulator with limited processing capability. That is, we cannot set an overlarge N_S, since this inappropriate setting would demand high computational complexity and take a tremendous amount of time to complete the simulation. Moreover, the computational load might also excess the memory of the simulator.

2) GENERATE RANDOM SAMPLES

As we utilize MATLAB in this course design, we can directly apply the functions embedded on MATLAB to generate random samples of a, θ, and $n(t)$. First, for the Rayleigh distributed a, we can either directly apply $a \leftarrow \texttt{raylrnd}(\sqrt{\mu/2})$ or indirectly construct a Rayleigh distributed random variable by the module of the sum of two Gaussian random variables by $a \leftarrow \sqrt{(\texttt{normrnd}(0, \sqrt{\mu/2}))^2 + (\texttt{normrnd}(0, \sqrt{\mu/2}))^2}$. It is recommended to master the indirect method for generating random variables, as there might not always exist an embedded generating function on MATLAB for all kinds of random variables. Therefore, one should know how to construct the generating function of sophisticated random variables by a set of generating functions of simple random variables. Similarly, the uniformly distributed θ can be constructed by modifying the embedded MATLAB function `rand` and applying $\theta \leftarrow 2 * \texttt{pi} * \texttt{rand}$, and the complex AWGN term $n(t)$ is structured by $n(t) \leftarrow \texttt{normrnd}(0, \sqrt{N_0/2}) + \texttt{j} * \texttt{normrnd}(0, \sqrt{N_0/2})$. Let $\mu = 1$ and $P_t/N_0 = 10$ dB, we plot the randomly generated $ae^{j\theta}$ and $n(t)$ when $\mathsf{N}_S = 1000$ in the complex plane in Fig. 3 for illustration

[2]The direct setup regulates N_S to be a fixed number, while the indirect setup specifies certain conditions and terminates the repeated trials with a variable number of N_S when the specified conditions are satisfied, e.g., the number of collected error events has reached a threshold. The direct setup is simple and straightforward, but the indirect setup is more efficient and reliable in most cases. For simplicity, we adopt the direct setup of N_S in the following simulations.

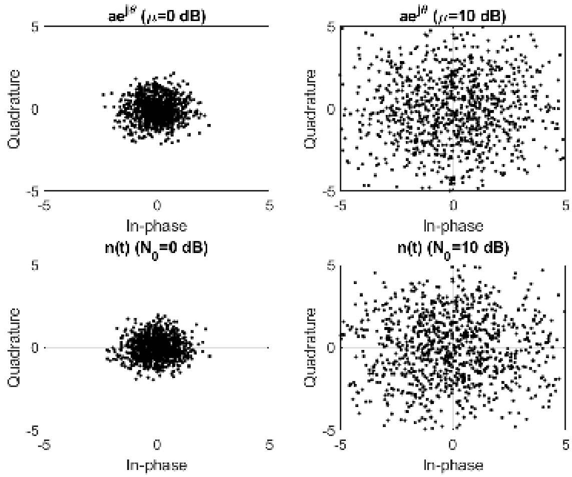


FIGURE 3. **Randomly generated samples of $ae^{j\theta}$ and $n(t)$, given $\mathsf{N}_S = 10^3$, $\mu = 1$, and $P_t/N_0 = 10$ dB.**

purposes. Then, we again utilize `rand`, the embedded function on MATLAB, to generate random samples of $x_B(t)$ by a simple code block with if-else structure infra

```
x_B(t) ← rand;
if(x_B(t) > 0.5)   x_B(t) ← 1;
else               x_B(t) ← −1;   end
```

3) PROCESS RANDOM SAMPLES BY DETERMINISTIC PROCEDURES

After generating random samples of $ae^{j\theta}$, $n(t)$, and $x_B(t)$, we can process these random samples by deterministic procedures. First, we simulate the baseband transmission procedure by (6) and obtain the dependent random samples of $y_B(t)$. Then, we simulate the ML estimation procedure defined in (11) to further process the dependent random samples of $y_B(t)$ and obtain the dependent random samples of $\hat{x}_B(t)$. For visualization purposes, we equalize the dependent random samples of baseband received signals $y_B(t)$ over normalized Rayleigh fading channel with different P_t/N_0 and show them in Fig. 4, given $\mathsf{N}_S = 10^3$ and $\mu = 1$. In particular, we utilize black dot and red cross markers to represent received normalized signals that are correctly and erroneously estimated, respectively. Also, red solid circle markers are employed to denote the ML estimation benchmarks, i.e., the elements in the signal space $\{\chi_1, \chi_0\}$. From this figure, it can be visualized that how channel fading and noise jointly contaminate the transmitted signals and why increasing transmit power P_t can mitigate these impairments. Meanwhile, by processing the dependent random samples of $y_B(t)$, we are also able to obtain the random sample of the SNR $\gamma(t)$ corresponding to each sample of $y_B(t)$ according to (8).

4) AGGREGATE THE PROCESSED NUMERICAL RESULTS

Then, by processing the independent random samples and acquiring several dependent random samples, we are now

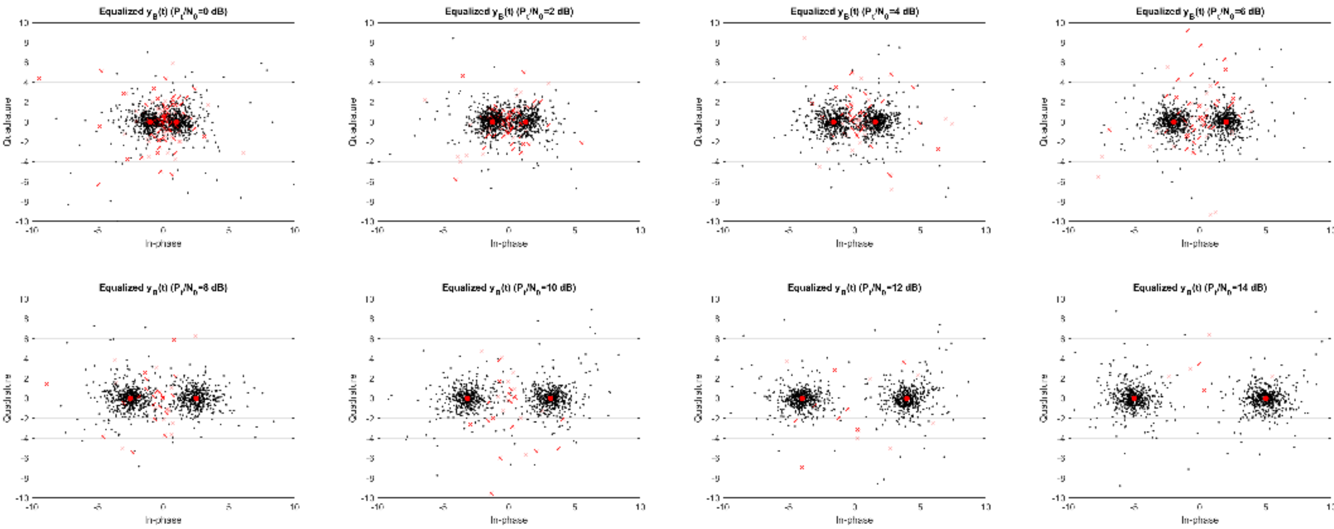
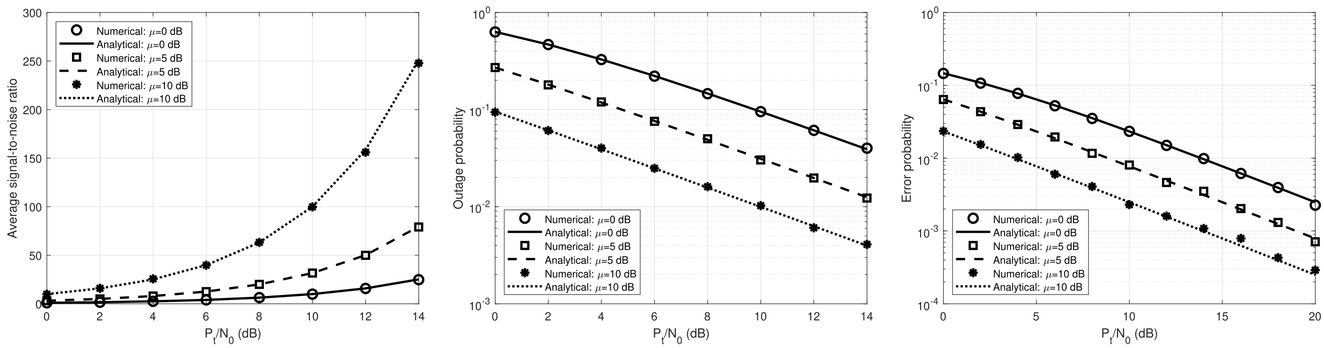


FIGURE 4. Equalized samples of $y_B(t)$ received over normalized Rayleigh fading channel with different P_t/N_0, given $\mathsf{N}_S = 10^3$ and $\mu = 1$. Black dot and red cross markers represent received normalized signals that are correctly and erroneously estimated, respectively. Red solid circle markers denote the ML estimation benchmarks, i.e., the elements in the signal space $\{\chi_1, \chi_0\}$.



(a) Average SNR (b) Outage probability (c) Error probability

FIGURE 5. Verification of the analytical expressions presented in Section IV-B by numerical results generated by Monte Carlo simulations, given $\mathsf{N}_S = 10^5$ and $R_{\text{th}} = 1$.

able to aggregate the numerical results and use them to verify our analytical expressions given in Section IV-B. To be clear, when comparing to the analytical expressions, we denote the nth random sample of $y_B(t)$, $x_B(t)$, $\hat{x}_B(t)$, and $\gamma(t)$ as $\mathsf{y}_B[n]$, $\mathsf{x}_B[n]$, $\hat{\mathsf{x}}_B[n]$, and $\mathsf{SNR}[n]$, respectively. Therefore, the numerical results of average SNR, outage probability, and error probability can be counted by

$$\overline{\mathsf{SNR}} = \frac{1}{\mathsf{N}_S} \sum_{n=1}^{\mathsf{N}_S} \mathsf{SNR}[n], \tag{16}$$

$$\mathsf{P}_o(R_{\text{th}}) = \frac{1}{\mathsf{N}_S} \sum_{n=1}^{\mathsf{N}_S} \mathbb{I}\left\{\log_2(1+\mathsf{SNR}[n]) < R_{\text{th}}\right\}, \tag{17}$$

and

$$\mathsf{P}_e = \frac{1}{\mathsf{N}_S} \sum_{n=1}^{\mathsf{N}_S} \mathbb{I}\left\{\hat{\mathsf{x}}_B[n] \neq \mathsf{x}_B[n]\right\}, \tag{18}$$

where $\mathbb{I}\{\cdot\}$ denotes the Iverson function returning unity if the enclosed condition is fulfilled, or zero, otherwise. We plot both analytical and numerical results of these three performance evaluation metrics in Fig. 5. This figure clearly illustrates that the numerical and analytical results match each other very well, which verifies the derived analytical expressions given in (9), (10), and (13). The simulation precision of Monte Carlo methods is a function of N_S, which can be quantified by the goodness-of-fit and analyzed using Chebyshev's inequality [89].

E. SUMMARY OF MONTE CARLO METHODS

To summarize Monte Carlo methods as we described in the previous subsection, we have to fairly appraise the pros and cons. On the one hand, although, Monte Carlo methods are straightforward to implement and do not involve any complicated mathematical operation, the computational complexity and simulation time caused by processing repeated trials would be tremendous, especially when the simulated system becomes sophisticated. On the other hand, the advantages of Monte Carlo methods are the simplicity and robustness. As long as the system model has been properly constructed, the numerical results can be produced in a simple and reliable manner, while maintaining the randomness and robustness. Moreover, apart from using as a powerful verification tool, Monte Carlo methods provide an alternative way to quantitatively investigate wireless communication systems when the analytical expressions cannot be obtained.

V. TEACHING EXPERIMENT AND DATA ANALYSIS

A. BRIEF SUMMARY OF THE TEACHING EXPERIMENT

To verify the effectiveness of the proposed course design, we carried out a brief teaching experiment. As mentioned in Section I, the course can be delivered in the form of lecture series, special lectures, small-scale workshops, seminars, and individual tutorials. Considering simplicity, cost efficiency, and generality, our teaching experiment was carried out in the form of one-day seminar and involved 25 first-year graduate students enrolled in the subject of telecommunications with the School of Computer, Electronics and Information, Guangxi University. The seminar is named 'Introduction to the Basic Research Methodology in Wireless Communications'. To quantitatively evaluate the effectiveness of the course design, we proposed to use two methods for analysis:

1) Comparative analysis by tests before and after delivering the seminar
2) Course quality assessment

The former is used to evaluate the objective improvement in knowledge background of graduate students by attending the seminar, while the latter is employed to assess participants' subjective perception of the seminar and receive further suggestions to improve the course design. Analyzing the collected data from both methods, we can have good understanding of the effectiveness of the proposed course design and check whether the course objective and goals are achieved. For completeness, we attach the knowledge background test paper and the course quality assessment questionnaire in Appendix A and Appendix B, respectively.[3]

Considering the format and organization of the teaching experiment, the instructional techniques adopted include inquiry-based learning, group discussion, and independent study. Meanwhile, cooperative and cognitive learning, project-based learning, and portfolio development techniques can also be employed for a longer version of the course design. Overall, the cognitive skills and abilities expected to be acquired by the course attendees are: attendees can find and promote their graduate-level research topics with critical and independent thinking, and appraise and judge research works via expertise and a set of principles and methods.

B. SEMINAR SCHEDULE AND LECTURE STRUCTURES

The seminar schedule is presented as follows for clarity:

- 09:00-09:40: Knowledge background test before seminar

[3]To avoid the unnecessary misunderstanding caused by language barrier, the entire teaching experiment, including seminar, tests, and questionnaire are delivered in a bilingual manner (Mandarin Chinese and English).

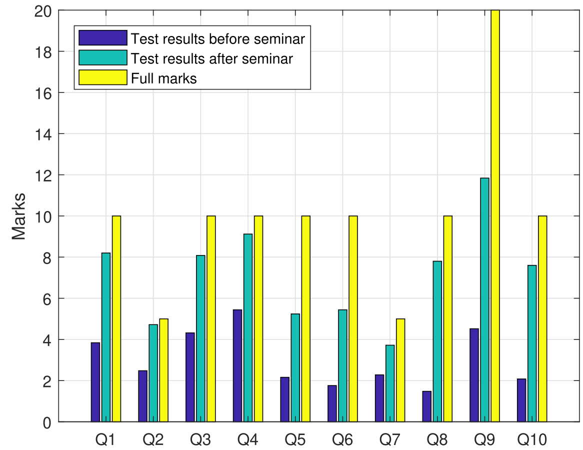


FIGURE 6. Knowledge background test results before and after delivering the one-day seminar.

- 10:00-10:40: Lecture I: Fundamentals of Wireless Communications: Objects, Strategies, and Methodology
- 11:00-11:40: Lecture II: System Modeling and Performance Analysis in Wireless Communications
- 14:30-15:10: Lecture III: Verification by Numerical Simulation and Monte Carlo Methods
- 15:10-15:30: Open discussion and Q&A sessions
- 15:50-16:30: Knowledge background test after seminar
- 16:30-16:50: Filling in course quality assessment questionnaire

To be comprehensive, we also give the lecture structures vis-à-vis Lecture I, II, and III infra:

1) LECTURE I: FUNDAMENTALS OF WIRELESS COMMUNICATIONS: OBJECTS, STRATEGIES, AND METHODOLOGY

- Architecture of a generic wireless communication system (5 minutes)
- Research objects (10 minutes)
- General research strategies (5 minutes)
- Research progress from a basic idea to a published work (5 minutes)
- Basic research methodology (10 minutes)
- Q&A (5 minutes)

2) LECTURE II: SYSTEM MODELING AND PERFORMANCE ANALYSIS IN WIRELESS COMMUNICATIONS

- System and channel modeling (10 minutes)
- What is performance evaluation metrics? (5 minutes)
- Performance analysis (10 minutes)
- What is the closed-form expression? (5 minutes)
- System optimization and resource allocation (5 minutes)
- Q&A (5 minutes)

3) LECTURE III: VERIFICATION BY NUMERICAL SIMULATION AND MONTE CARLO METHODS

- How can we know whether the derived analytical expressions are correct? (5 minutes)

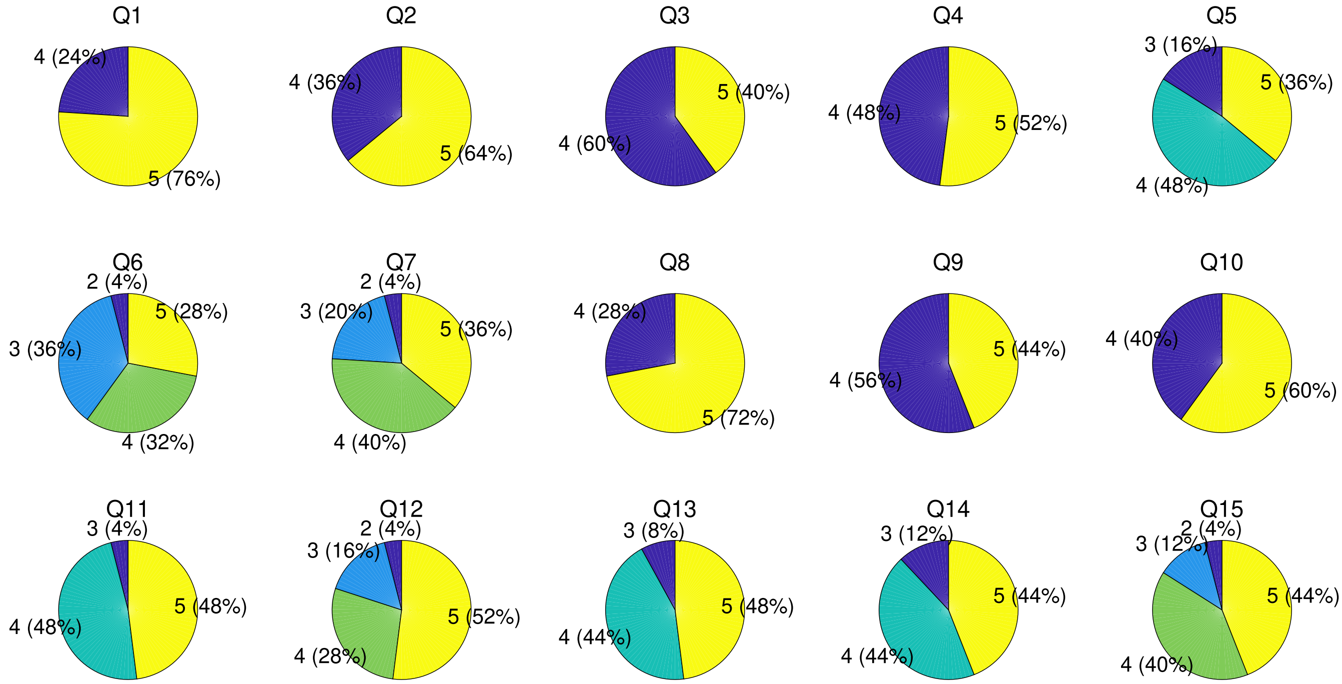


FIGURE 7. Subjective data collections of Q1-Q15 in the questionnaire.

- Numerical simulation and Monte Carlo methods (5 minutes)
- Implement a Monte Carlo simulation by MATLAB (15 minutes)
- Comparison between analytical and numerical results and discussion (5 minutes)
- Summary of Monte Carlo methods (5 minutes)
- Q&A (5 minutes)

C. DATA ORGANIZATION AND STATISTICAL ANALYSIS

We collected the quantitative data from the comparison tests before and after delivering the seminar as well as the anonymous survey, which are presented in Fig. 6, Fig. 7, and Fig. 8. To ease the data analysis, we also summarize the detailed information regarding the comparison tests in Table 1.

TABLE 1. Objective data collections of knowledge background tests before and after delivering the one-day seminar.

Questions	Average marks before	Average marks after	Growth rates	Contribution percentages
Q1	3.84	8.20	113.54%	10.53%
Q2	2.48	4.72	90.32%	5.41%
Q3	4.32	8.08	87.04%	9.08%
Q4	5.44	9.12	67.65%	8.89%
Q5	2.16	5.24	142.59%	7.44%
Q6	1.76	5.44	209.09%	8.89%
Q7	2.28	3.72	63.16%	3.48%
Q8	1.48	7.80	427.03%	15.27%
Q9	4.52	11.84	161.95%	17.68%
Q10	2.08	7.60	265.38%	13.33%
Total	30.36	71.76	136.36%	100.00%

From Fig. 6 and Table 1, we have the key findings as follows. First of all, it is demonstrated that our course structure design works, as the average marks for all questions have considerably increased by 136.36% after giving the lectures. Second, we find that most students have basically known what the research objects and possible ways to discover potential research directions are in wireless communications, but not comprehensively. Also, we can see that most students can point out at least one state-of-the-art communication technology in 5G, which indicates that they are tracking the research front in their specific fields. Meanwhile, most students are also able to give several performance evaluation metrics and have basic understanding of performance analysis in the context of wireless communications. However, some of them misunderstood the concept of system optimization. Plus, most students have good understanding of system modeling but cannot provide the details of how to model a wireless communication system. Similarly, the concept of fading is well known among students, but only a few of them can well explain what small-scale fading is. Unfortunately, most students misunderstand the concept of closed-form expression and cannot provide detailed methodology for result verification, and even do not explicitly know Monte Carlo methods.

Also, from Fig. 7 and Fig. 8, we are glad to see that most students are basically satisfied with the course structure and find it helpful, as all students give overall scores of 4 (28%) or 5 (72%). More importantly, 66% students have never attended a similar course for research methodology like ours and 100% students will recommend their colleagues or classmates attending such a methodological course in the future. From the data presented in Fig. 7 and the answers to

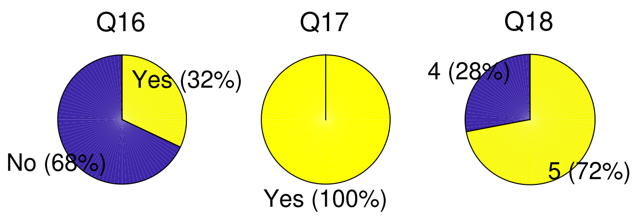


FIGURE 8. Subjective data collections of Q16-Q18 in the questionnaire.

Q19 and Q20, we summarize the strengths and weaknesses of the course structure as follows. The strengths include:

- The course is well defined and organized in a logical manner.
- The course contents are delivered in an easy-to-understand way, so as most students can understand them well.
- It is appreciated that mathematical software is introduced with proper examples.
- Having fewer equations help students understand better.

The weaknesses include:

- The course is too short to explain all new concepts well.
- More examples should be given to enhance understanding of the research methodology.
- A practical research example should be provided, which is related to 5G and industry.
- The course needs to be more interactive and more time should be given to students to think.
- Experimental verification and system-level testbed are recommended being added in the future course.
- The course could be broader for all types communications (e.g., wired communications and acoustic communications), instead of only focusing on wireless communications based on electromagnetic wave.

VI. CONCLUSIONS AND FUTURE IMPROVEMENT DIRECTIONS

In this paper, we presented an introductory course design for fresh research-based graduate students, which is planned to be delivered immediately after enrollment. The course aims at covering necessary research methodologies and the rudiments of wireless communications to research-based graduate students. Due to the target student groups, the course structure has been tailored accordingly and is based on simulations. Simple but insightful examples were provided to demonstrate the application of the basic research methodology in wireless communications. Specifically, average SNR, outage probability, and error probability were investigated and visualized via MATLAB. The objective and subjective data collected from the teaching experiment have verified the effectiveness of the course structure design. By participating in this course, research-based graduate students are expected to gain preliminary knowledge of the research methodology and strategies in the field of wireless communication and have the first taste of research life.

In addition, throughout the conducted teaching experiment, we also found a number of future improvement directions of the course design, which are summarized as follows:

- Apart from the form of one-day seminar, the course can also be delivered in other forms. It is worth expanding and designing a one-semester course module to cover more technological details and profound discussions regarding the basic research methodology in wireless communications.
- By expanding the course duration, the course structure design would also be improved and provide more insights to graduate students if supplementing practical demonstration using software-defined radio (SDR) equipment and GNU-radio software development toolkit.
- It is worth delivering the course with an open research project for each individual or in group, especially when the course duration becomes longer. By such an open research project, graduate students have an opportunity to apply the basic research methodology learned from this course.

Based on the feedback received from the course attendees and our experience, we further recommend a one-semester (lasting from 12 weeks to 16 weeks) course module structure with practical experiments and open research project as follows:

- Week 1: Fundamental concepts and research objects (coursework-summarizing the history of modern wireless communications)
- Week 2: 5G and beyond (optional)
- Week 3: Research strategies and examples
- Week 4: Basic research methodology
- Week 5: Research directions and literature review (coursework-preparing a research proposal accompanying a proper literature review)
- Week 6: Common research challenges (optional)
- Week 7: System modeling (coursework-constructing a system model according to the research proposal)
- Week 8: Common assumptions adopted for simplifying system models (optional)
- Week 9: Performance analysis and optimization (coursework-carrying out performance analysis and/or optimization based on the constructed system model)
- Week 10: Numerical verification and simulation
- Week 11: Useful software for research activities (coursework-numerically verifying the performance analysis by supporting data)
- Week 12: Experimental verification and system-level test
- Week 13: Individual discussion meeting I (coursework-preparing the outline of a research paper according to the research proposal and collected analytical and numerical data)
- Week 14: Introduction to academic writing (optional)
- Week 15: Individual discussion meeting II (coursework-preparing the first draft of the research paper)
- Week 16: Oral presentation and project demonstration

APPENDIX A
KNOWLEDGE BACKGROUND TEST PAPER

Please answer the following questions in a closed-book and independent manner within 40 minutes

1) Please explain what the research objects in wireless communications are. (10 marks)
2) Please provide three possible ways to discover potential research directions. (5 marks)
3) Please specify five state-of-the-art communications technologies in 5G and beyond. (10 marks)
4) Please specify five performance evaluation metrics for characterizing a generic wireless communication system. (10 marks)
5) Please explain the concept of system modeling in wireless communications and its procedure. (10 marks)
6) Please explain the concept of small-scale channel fading and specify three small-scale channel fading models. (10 marks)
7) Please explain the concepts of performance analysis and system optimization in the context of wireless communications. (5 marks)
8) Please explain what a closed-form expression is. (10 marks)
9) Please explain how we can verify an analytical expression/result obtained by mathematical derivations. (20 marks)
10) Please explain what Monte Carlo method is. (10 marks)

APPENDIX B
COURSE QUALITY ASSESSMENT QUESTIONNAIRE

Please fill in the following questionnaire (1: completely disagree; 2: disagree; 3: neutral; 4: agree; 5: completely agree).

1) The objective and aims of this course are clearly defined. (1, 2, 3, 4, 5)
2) The course structure is well designed. (1, 2, 3, 4, 5)
3) New concepts introduced in the course are well explained. (1, 2, 3, 4, 5)
4) The teaching and instructional materials and tools are helpful. (1, 2, 3, 4, 5)
5) The course is interesting. (1, 2, 3, 4, 5)
6) The course is challenging. (1, 2, 3, 4, 5)
7) The prerequisite for this course is high. (1, 2, 3, 4, 5)
8) The course delivered new and useful knowledge that I did not know before. (1, 2, 3, 4, 5)
9) By attending this course, I have had a basic idea what research is in the field of wireless communications. (1, 2, 3, 4, 5)
10) By attending this course, I have gained insights into the research objects, challenges, strategies, and methodology in wireless communications. (1, 2, 3, 4, 5)
11) By attending this course, I have gained some basics for carrying out performance analysis and optimization in the field of wireless communications. (1, 2, 3, 4, 5)
12) By attending this course, I have picked up some basic skills to use certain mathematical and software tools for research. (1, 2, 3, 4, 5)
13) By attending this course, I have mastered the concepts of analytical and numerical results as well as their relation. (1, 2, 3, 4, 5)
14) By attending this course, I have known how to verify analytical results by numerical simulations based on Monte Carlo methods. (1, 2, 3, 4, 5)
15) By attending this course, I have gained some ideas of how to advance my own research project. (1, 2, 3, 4, 5)
16) Have you enrolled into a similar methodological course before? (Yes or No)
17) Will you recommend your colleagues or classmates attending such a methodological course in the future? (Yes or No)
18) Please give an overall score of this methodological course. (1, 2, 3, 4, 5 from lowest to highest)
19) List three merits and three drawbacks of the course.
20) Do you have any further suggestion and comment on the course in all aspects?

ACKNOWLEDGMENT

We thank the editor and the anonymous reviewers for their constructive comments, which have helped us improve the quality of the paper.

REFERENCES

[1] H. Nyquist, "Certain topics in telegraph transmission theory," *Trans. Amer. Inst. Electr. Eng.*, vol. 47, no. 2, pp. 617–644, Apr. 1928.

[2] C. E. Shannon, "A mathematical theory of communication," *Bell Syst. Tech. J.*, vol. 27, no. 3, pp. 379–423, Jul./Oct. 1948.

[3] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[4] China Graduate Student Admission Information Website. *Report of Admission Data Analysis of Chinese Master Students: 2015–2018*. (in Chinese). Accessed: Mar. 8, 2019. [Online]. Available: https://yz.chsi.com.cn/yzzt/fxbg2018

[5] P. M. Shankar and B. A. Eisenstein, "Project-based instruction in wireless communications at the junior level," *IEEE Trans. Educ.*, vol. 43, no. 3, pp. 245–249, Aug. 2000.

[6] A. J. Lopez-Martin, "Teaching random signals and noise: An experimental approach," *IEEE Trans. Educ.*, vol. 47, no. 2, pp. 174–179, May 2004.

[7] E. M. Belding-Royer, "Escape from the computer lab: Education in mobile wireless networks," in *Proc. IEEE PerCom*, Orlando, FL, USA, Mar. 2004, pp. 231–235.

[8] L. A. DaSilva, S. F. Midkiff, and I. Chen, "A hands-on course on wireless and mobile systems design," in *Proc. IEEE PerCom*, Orlando, FL, USA, Mar. 2004, pp. 241–246.

[9] S. F. Midkiff, "An experiential course in wireless networks and mobile systems," *IEEE Pervas. Comput.*, vol. 4, no. 1, pp. 9–13, Jan. 2005.

[10] S. Guzelgoz and H. Arslan, "A wireless communications systems laboratory course," *IEEE Trans. Educ.*, vol. 53, no. 4, pp. 532–541, Nov. 2010.

[11] N. I. Sarkar and T. M. Craig, "Teaching wireless communication and networking fundamentals using Wi-Fi projects," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 98–104, Feb. 2006.

[12] G. S. Prabhu and P. M. Shankar, "Simulation of flat fading using MATLAB for classroom instruction," *IEEE Trans. Educ.*, vol. 45, no. 1, pp. 19–25, Feb. 2002.

[13] T. Li and H. Zhu, "Analysis and simulation of Nakagami fading channel with MATLAB," in *Proc. IEEE CEEM*, Hangzhou, China, Nov. 2003, pp. 490–494.

[14] J. Proakis and M. Salehi, *Digital Communications*. New York, NY, USA: McGraw-Hill, 2008.

[15] M. Simon and M. Alouini, *Digital Communication over Fading Channels* (Wiley Series in Telecommunications and Signal Processing). Hoboken, NJ, USA: Wiley, 2005.

[16] D. Tse and P. Viswanath, *Fundamentals Wireless Communication* (Wiley Series in Telecommunications). Cambridge, U.K.: Cambridge Univ. Press, 2005.

[17] L. Peng, "The discussion about the national college communication engineering students' question of taking the entrance exams for postgraduate schools," (in Chinese), *J. Southwest Univ. Nationalities, Natural Sci. Ed.*, vol. 37, pp. 15–20, May 2011.

[18] Y. Geng, "On contradictions in quality development of postgraduate education," (in Chinese), *J. Graduate Edu.*, vol. 49, no. 1, pp. 14–18, Feb. 2019.

[19] J. Proakis, M. Salehi, and G. Bauch, *Contemporary Communication Systems Using MATLAB*. Boston, MA, USA: Cengage Learning, 2012.

[20] S. Dang, G. Chen, and J. P. Coon, "Outage performance analysis of full-duplex relay-assisted device-to-device systems in uplink cellular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 4506–4510, May 2017.

[21] S. Dang, J. P. Coon, and G. Chen, "Outage performance of two-hop OFDM systems with spatially random decode-and-forward relays," *IEEE Access*, vol. 5, pp. 27514–27524, 2017.

[22] S. Dang, G. Chen, and J. P. Coon, "Multicarrier relay selection for full-duplex relay-assisted OFDM D2D systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7204–7218, Aug. 2018.

[23] E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, "Index modulation techniques for next-generation wireless networks," *IEEE Access*, vol. 5, pp. 16693–16746, 2017.

[24] F. Boccardi, B. Clerckx, A. Ghosh, E. Hardouin, G. Jöngren, K. Kusume, E. Onggosanusi, and Y. Tang, "Multiple-antenna techniques in LTE-advanced," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 114–121, Mar. 2012.

[25] J. Ketonen, M. Juntti, and J. R. Cavallaro, "Performance-complexity comparison of receivers for a LTE MIMO-OFDM system," *IEEE Trans. Signal Process.*, vol. 58, no. 6, pp. 3360–3372, Jun. 2010.

[26] J. G. Andrews, "Interference cancellation for cellular systems: A contemporary overview," *IEEE Wireless Commun*, vol. 12, no. 2, pp. 19–29, Apr. 2005.

[27] H. Li, L. Han, R. Duan, and G. M. Garner, "Analysis of the synchronization requirements of 5G and corresponding solutions," *IEEE Commun. Standards Mag.*, vol. 1, no. 1, pp. 52–58, Mar. 2017.

[28] J. Zhong, G. Chen, J. Mao, S. Dang, and P. Xiao, "Iterative frequency domain equalization for MIMO-GFDM systems," *IEEE Access*, vol. 6, pp. 19386–19395, 2018.

[29] H. Minn and N. Al-Dhahir, "Optimal training signals for MIMO OFDM channel estimation," *IEEE Trans. Wireless Commun.*, vol. 5, no. 5, pp. 1158–1168, May 2006.

[30] Z. Gao, L. Dai, Z. Wang, and S. Chen, "Spatially common sparsity based adaptive channel estimation and feedback for FDD massive MIMO," *IEEE Trans. Signal Process.*, vol. 63, no. 23, pp. 6169–6183, Dec. 2015.

[31] Z. Gao, L. Dai, W. Dai, B. Shim, and Z. Wang, "Structured compressive sensing-based spatio-temporal joint channel estimation for FDD massive MIMO," *IEEE Trans. Commun.*, vol. 64, no. 2, pp. 601–617, Feb. 2016.

[32] S. Dang, J. P. Coon, and G. Chen, "An equivalence principle for OFDM-based combined bulk/per-subcarrier relay selection over equally spatially correlated channels," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 122–133, Jan. 2017.

[33] M. Rahriema and Y. Antia, "Optimum soft decision decoding with channel state information in the presence of fading," *IEEE Commun. Mag.*, vol. 35, no. 7, pp. 110–111, Jul. 1997.

[34] R. Di Taranto, S. Muppirisetty, R. Raulefs, D. Slock, T. Svensson, and H. Wymeersch, "Location-aware communications for 5G networks: How location information can improve scalability, latency, and robustness of 5G," *IEEE Signal Process. Mag.*, vol. 31, no. 6, pp. 102–112, Nov. 2014.

[35] G. Chen, Z. Tian, Y. Gong, Z. Chen, and J. A. Chambers, "Max-ratio relay selection in secure buffer-aided cooperative wireless networks," *IEEE Trans. Inf. Forensics Security*, vol. 9, no. 4, pp. 719–729, Apr. 2014.

[36] Z. Gao, L. Dai, C. Yuen, and Z. Wang, "Asymptotic orthogonality analysis of time-domain sparse massive MIMO channels," *IEEE Commun. Lett.*, vol. 19, no. 10, pp. 1826–1829, Oct. 2015.

[37] M. Wen, X. Cheng, M. Ma, B. Jiao, and H. V. Poor, "On the achievable rate of OFDM with index modulation," *IEEE Trans. Signal Process.*, vol. 64, no. 8, pp. 1919–1932, Apr. 2016.

[38] S. Guo, H. Zhang, and M.-S. Alouini, "MIMO capacity with reduced RF chains," 2019, *arXiv:1901.03893*. [Online]. Available: https://arxiv.org/abs/1901.03893

[39] M. Pejanovic-Djurisic, E. Kocan, and R. Prasad, *OFDM Based Relay Systems for Future Wireless Communications*. Aalborg, Denmark: River, 2012.

[40] G. Chen, Y. Gong, and J. Chambers, "Study of relay selection in a multi-cell cognitive network," *IEEE Wireless Commun. Lett.*, vol. 2, no. 4, pp. 435–438, Aug. 2013.

[41] M. Wen, B. Ye, E. Basar, Q. Li, and F. Ji, "Enhanced orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4786–4801, Jul. 2017.

[42] Q. Li, M. Wen, E. Basar, H. V. Poor, B. Zheng, and F. Chen, "Diversity enhancing multiple-mode OFDM with index modulation," *IEEE Trans. Commun.*, vol. 66, no. 8, pp. 3653–3666, Aug. 2018.

[43] S. Dang, G. Chen, and J. P. Coon, "Outage performance of two-hop OFDM with index modulation and multi-carrier relay selections," *IEEE Wireless Commun. Lett.*, vol. 7, no. 6, pp. 926–929, Dec. 2018.

[44] G. Sheng, S. Dang, Z. Zhang, E. Kocan, and M. Pejanovic-Djurisic, "OFDM with index modulation assisted by multiple amplify-and-forward relays," *IEEE Wireless Commun. Lett.*, vol. 8, no. 3, pp. 789–792, Jun. 2019.

[45] G. Chen, J. P. Coon, and M. Di Renzo, "Secrecy outage analysis for downlink transmissions in the presence of randomly located eavesdroppers," *IEEE Trans. Inf. Forensics Security*, vol. 12, no. 5, pp. 1195–1206, May 2017.

[46] G. Chen, Y. Gong, P. Xiao, and J. A. Chambers, "Physical layer network security in the full-duplex relay system," *IEEE Trans. Inf. Forensics Security*, vol. 10, no. 3, pp. 574–583, Mar. 2015.

[47] G. Chen, J. P. Coon, and S. E. Tajbakhsh, "Secure routing for multihop ad hoc networks with inhomogeneous eavesdropper clusters," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 10660–10670, Nov. 2018.

[48] T. M. Nguyen, V. N. Ha, and L. B. Le, "Resource allocation optimization in multi-user multi-cell massive MIMO networks considering pilot contamination," *IEEE Access*, vol. 3, pp. 1272–1287, 2015.

[49] S. Dang, J. P. Coon, and G. Chen, "Resource allocation for full-duplex relay-assisted device-to-device multicarrier systems," *IEEE Wireless Commun. Lett.*, vol. 6, no. 2, pp. 166–169, Apr. 2017.

[50] S. Dang, G. Chen, and J. P. Coon, "Lexicographic codebook design for OFDM with index modulation," *IEEE Trans. Wireless Commun.*, vol. 17, no. 12, pp. 8373–8387, Dec. 2018.

[51] T. Rondeau and C. Bostian, *Artificial Intelligence in Wireless Communications* (Artech House Mobile Communications Series). Norwood, MA, USA: Artech House, 2009.

[52] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May 2016.

[53] Q. Li, G. Li, W. Lee, M.-I. Lee, D. Mazzarese, B. Clerckx, and Z. Li, "MIMO techniques in WiMAX and LTE: A feature overview," *IEEE Commun. Mag.*, vol. 48, no. 5, pp. 86–92, May 2010.

[54] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[55] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: Opportunities, challenges and the path to market," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 26–32, Dec. 2013.

[56] R. Y. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2228–2241, Jul. 2008.

[57] L. Dai, B. Wang, Y. Yuan, S. Han, C.-L. I, and Z. Wang, "Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015.

[58] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block coding for wireless communications: Performance results," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 3, pp. 451–460, Mar. 1999.

[59] M.-S. Alouini and A. J. Goldsmith, "A unified approach for calculating error rates of linearly modulated signals over generalized fading channels," *IEEE Trans. Commun.*, vol. 47, no. 9, pp. 1324–1334, Sep. 1999.

[60] Z. Wang and G. B. Giannakis, "A simple and general parameterization quantifying performance in fading channels," *IEEE Trans. Commun.*, vol. 51, no. 8, pp. 1389–1398, Aug. 2003.

[61] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: Challenges, opportunities, and implementation," *Proc. IEEE*, vol. 102, no. 1, pp. 56–103, Jan. 2014.

[62] J. Jeganathan, A. Ghrayeb, and L. Szczecinski, "Spatial modulation: Optimal detection and performance analysis," *IEEE Commun. Lett.*, vol. 12, no. 8, pp. 545–547, Aug. 2008.

[63] T. L. Narasimhan and A. Chockalingam, "On the capacity and performance of generalized spatial modulation," *IEEE Commun. Lett.*, vol. 20, no. 2, pp. 252–255, Feb. 2016.

[64] P. Liu, M. Di Renzo, and A. Springer, "Line-of-sight spatial modulation for indoor mmWave communication at 60 GHz," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7373–7389, Nov. 2016.

[65] H. S. Hussein, H. Esmaiel, and D. Jiang, "Fully generalised spatial modulation technique for underwater communication," *Electron. Lett.*, vol. 54, no. 14, pp. 907–909, 2018.

[66] M. Di Renzo and H. Haas, "Bit error probability of space modulation over Nakagami-*m* fading: Asymptotic analysis," *IEEE Commun. Lett.*, vol. 15, no. 10, pp. 1026–1028, Oct. 2011.

[67] R. Rajashekar, K. V. S. Hari, and L. Hanzo, "Antenna selection in spatial modulation systems," *IEEE Commun. Lett.*, vol. 17, no. 3, pp. 521–524, Mar. 2013.

[68] M. Wen, X. Cheng, Y. Bian, and H. V. Poor, "A low-complexity near-ML differential spatial modulation detector," *IEEE Signal Process. Lett.*, vol. 22, no. 11, pp. 1834–1838, Nov. 2015.

[69] E. Basar, U. Aygolu, E. Panayirci, and H. V. Poor, "Performance of spatial modulation in the presence of channel estimation errors," *IEEE Commun. Lett.*, vol. 16, no. 2, pp. 176–179, Feb. 2012.

[70] N. Serafimovski, A. Younis, R. Mesleh, P. Chambers, and M. Di Renzo, "Practical implementation of spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4511–4523, Nov. 2013.

[71] P. Yang, M. Di Renzo, Y. Xiao, S. Li, and L. Hanzo, "Design guidelines for spatial modulation," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 6–26, 1st Quart., 2015.

[72] Y. Yang, D. Fei, and S. Dang, "Inter-vehicle cooperation channel estimation for IEEE 802.11p V2I communications," *J. Commun. Netw.*, vol. 19, no. 3, pp. 227–238, Jun. 2017.

[73] J. Zhao, S. Dang, and Z. Wang, "Full-duplex relay-assisted orthogonal frequency-division multiplexing with index modulation," *IEEE Syst. J.*, to be published.

[74] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4296–4307, Dec. 2012.

[75] M. Dohler, R. W. Heath, Jr., A. Lozano, C. B. Papadias, and R. B. Valenzuela, "Is the PHY layer dead?" *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 159–165, Apr. 2011.

[76] M. Kalos and P. Whitlock, *Monte Carlo Methods*. Hoboken, NJ, USA: Wiley, 2009.

[77] D. Wan, M. Wen, F. Ji, H. Yu, and F. Chen, "On the achievable sum-rate of NOMA-based diamond relay networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1472–1486, Feb. 2019.

[78] J. M. Borwein and R. E. Crandall, "Closed forms: What they are and why we care," *Notices AMS*, vol. 60, no. 1, pp. 50–65, 2013.

[79] H. Ren, N. Liu, C. Pan, M. Elkashlan, A. Nallanathan, X. You, and L. Hanzo, "Power- and rate-adaptation improves the effective capacity of C-RAN for Nakagami-*m* fading channels," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 10841–10855, Nov. 2018.

[80] B. Lee, D. Park, and H. Seo, *Wireless Communications Resource Management*. Hoboken, NJ, USA: Wiley, 2009.

[81] J. Tang, G. Chen, and J. P. Coon, "Joint coverage enhancement by power allocation in poisson clustered out-of-band D2D networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 11537–11548, Dec. 2018.

[82] I. Comsa and R. Trestian, "Next-generation wireless networks meet advanced machine learning applications," in *Advances in Wireless Technologies and Telecommunication*. Hershey, PA, USA: IGI Global, 2019.

[83] N. Kostov, "Mobile radio channels modeling in MATLAB," *Radio Eng.*, vol. 12, no. 4, pp. 12–17, 2003.

[84] M. Novey, T. Adali, and A. Roy, "A complex generalized Gaussian distribution—Characterization, generation, and estimation," *IEEE Trans. Signal Process.*, vol. 58, no. 3, pp. 1427–1433, Mar. 2010.

[85] A. Jeffrey and D. Zwillinger, *Table of Integrals, Series and Products*. Amsterdam, The Netherlands: Elsevier, 2007.

[86] M. Abramowitz and I. Stegun, *Handbook of Mathematical Functions: With Formulas, Graphs, and Mathematical Tables* (Dover Books on Mathematics). New York, NY, USA: Dover, 2012.

[87] F. Olver, D. Lozier, R. Boisvert, and C. Clark, *NIST Handbook of Mathematical Functions*. Cambridge, U.K.: Cambridge Univ. Press, 2010.

[88] M. Jeruchim, P. Balaban, and K. Shanmugan, "Simulation of communication systems: Modeling, methodology and techniques," in *Information Technology: Transmission, Processing and Storage*. New York, NY, USA: Springer, 2006.

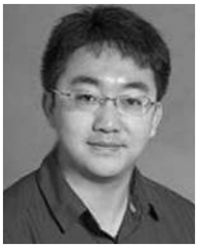
[89] N. Henze, "Empirical-distribution-function goodness-of-fit tests for discrete models," *Can. J. Statist.*, vol. 24, no. 1, pp. 81–93, 1996.

ZHONGLI WANG graduated in communication engineering and control theory and control engineering from the University of Science and Technology Beijing. He is currently an Associate Professor with the College of Electrical and Information Engineering, Beihua University. He dedicates to the investigations of wireless communications, signal processing, pattern recognition, and embedded systems. He published ten papers in international journals and proceedings and wrote three textbooks. He also participated in two research projects sponsored by the National Natural Science Foundation of China, four research projects sponsored by the local municipal government and three research projects sponsored by Beihua University.

SHUPING DANG (S'13–M'18) received the B.Eng. degree (Hons) in electrical and electronic engineering from The University of Manchester, the B.Eng. degree in electrical engineering and automation from Beijing Jiaotong University, in 2014, via a joint 2+2 dual-degree program, and the D.Phil. degree in engineering science from the University of Oxford, in 2018. He joined the R&D Center, Huanan Communication Company Ltd., after graduating from the University of Oxford. He is currently a Postdoctoral Fellow with the Computer, Electrical and Mathematical Science and Engineering Division, King Abdullah University of Science and Technology (KAUST). His current research interests include novel modulation schemes, cooperative communications, and 6G wireless network design. He serves as a Reviewer for a number of key journals in communications and information science, including the IEEE Transactions on Wireless Communications, the IEEE Transactions on Communications, the IEEE Wireless Communications Letters, the IEEE Communications Letters, and the IEEE Transactions on Vehicular Technology.

SINA SHAHAM received the B.Eng. degree (Hons) in electrical and electronic engineering from The University of Manchester and the M.Sc. degree in engineering management from the University of Warwick. He is currently pursuing the M.Phil. degree with The University of Sydney. He has years of experience as a Data Scientist and Software Engineer in companies such as InDebted. His current research interest include the applications of artificial intelligence in big data and privacy.

ZHENRONG ZHANG (M'18) received the B.S. and M.S. degrees from the Electronics Department, Peking University, China, in 1998 and 2001, respectively, and the Ph.D. degree from Nanyang Technological University (NTU), Singapore, in 2006. He is currently a Postdoctoral Research Associate with the National Laboratory on Local Optic-fiber Communication Networks and Advanced Optical Communication Systems, Department of Electronics, Peking University, and also a Professor with the School of Computer, Electronic and Information, Guangxi University (GXU). He is also with the Guangxi Key Laboratory of Multimedia Communications and Network Technology. He has published more than 20 technical papers in journals and conferences. His research interests include survivability and restoration in optical networks, network design, and protocol development for optical networks and wireless communications.



ZHIHAN LV (M'16) received the Ph.D. degree from Paris Diderot University and the Ocean University of China, in 2012. He was a Research Associate with University College London. He has been an Assistant Professor with the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, since 2012. He was with CNRS, France, as a Research Engineer, with Umeå University/KTH Royal Institute of Technology, Sweden, as a Postdoctoral Research Fellow, and Fundación FIVAN, Spain, as an Experienced Researcher. He is currently an Associate Professor with Qingdao University. He has completed several projects successfully on PC, Website, smartphone, and smartglasses. His research interests include multimedia, augmented reality, virtual reality, computer vision, 3-D visualization and graphics, serious game, HCI, bigdata, and GIS. His research application fields widely range from everyday life to traditional research fields (i.e., geography, biology, and medicine). He was a Marie Curie Fellow with the European Union's Seventh Framework Programme LANPERCEPT.

Dr. Lv is a Program Committee Member of ACM IUI 2015 and 2016, IEEE BIGDATA4HEALTH Workshop 2016, IEEE/CIC WIN Workshop 2016, IIKI 2016, and WASA 2016. He has been an Associate Editor of *PLOS One* (since 2016), IEEE ACCESS (since 2016), *Neurocomputing* (since 2016), and *IET Image Processing* (since 2017), and is a Guest Editor of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, *Multimedia Tools and Applications*, *Neurocomputing*, and the *Journal of Intelligent and Fuzzy Systems*.