Prolog to the Section on Wireless Communications Technology

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I. PRACTICAL LIMITATIONS OF EXISTING STANDARDS

Recent fourth-generation (4G) wireless cellular systems hold the promise of hitherto unachievable data rates for their users, which would improve the already available services, while facilitating entirely new services. For example, 3-D holographic (http://www.holografika.com/) communication with several remote partners may revolutionize our everyday life at home, at work, simply everywhere. However, such high data rates might only be achieved under best wireless propagation conditions. In reality, the wireless channel as well as the multiuser and multipath interference limit the attainable throughput and the existing cellular transmission systems fail to live up to these expectations. In the paper presented in this section of the Centennial Special Issue of the Proceedings of the IEEE, we took a closer look at the existing third-generation (3G) systems in service and investigated their capabilities with the aid of measurements. While the theoretical throughput of these cellular systems is high, the existing standards fail to reach their full potential. The reasons for these limitations are multifold.

The authors take a look at the existing 3G systems in service and investigate the capabilities of 4G, and while the theoretical throughput of these cellular systems is expected to be high, the future promises to offer more technological improvements and innovations.

On the one hand, we still do not fully understand how to make best use of multiple-antenna-aided transmission systems, despite their 15-year evolution. In Section II of the paper, we categorize the associated performance losses into a few subclasses. Let us commence with the class of channel state information (CSI)-induced losses. The availability of accurate CSI at the transmitter may be expected to considerably improve the achievable throughput of the system, while its inaccurate knowledge would naturally erode the maximum attainable performance.

On the other hand, our concept of transmission systems is quite traditional and the legacy of existing systems does not allow for radical changes in the architecture of such transmission systems. This traditional thinking is also reflected in the fact that major players of the wireless industry, in particular the equipment manufacturers, have to agree to a common standard for the sake of interoperability. As everyone in this group of stakeholders has to ensure that they retain a fair market share, many technologically advanced ideas cannot be readily incorporated, since some companies would benefit more than others. Cellular standards are thus based on a carefully negotiated compromise, which might influence the direction of technological advances. We may refer to the performance limitations belonging to this class as design losses.

A further performance limitation of cellular systems depends on the specific implementation of the standardized transmission principles. While substantial technological advances have been achieved in recent years, there is still room for improving the quality of implementations. However, the specific design of the cellular transmission system and thus the ratified standards have a substantial impact on the associated design losses, simply because some solutions may be implemented more efficiently than

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others. Our results characterizing the emerging 4G systems suggest similar trends to those observed for the 3G systems. While absolute transmission rates of the 4G systems were further improved by using more spectrum and more antennas, the relative throughput losses may remain the same or might even be increased, hence leaving a range of challenges for the wireless research community to tackle. Some of these are detailed in Sections IV and V of the paper, complemented by a range of future challenges.

II. INTRODUCTION TO OPTICAL WIRELESS COMMUNICATIONS

The demand for wireless data communications is insatiable, with traffic doubling every few years, and users requiring "PC-like" capabilities from their smartphones or tablets. Ubiquitous access is becoming the norm. However, given the current infrastructure and the paucity of available bandwidth, it is becoming increasingly difficult to meet these demands. The radio-frequency (RF) spectrum is congested in the most valuable frequency bands that are capable of offering benevolent channel characteristics in terms of propagation properties and coverage. Multiple-input–multiple-output (MIMO) systems are being widely deployed to increase the capacity available but the "easy wins" in terms of improvements have already been gleaned. As detailed in Section III of the paper, the promising link level gains are often eroded in a multicell system deployment, especially in the absence of advanced techniques such as intelligent and practically realizable interference management.

These are lessons that have been learned, for example, from the trials of the so-called cooperative multicell processing (COMP) technique, which was submitted to the 3rd Generation Partnership Project's Long-Term Evolution (3GPP LTE) initiative. Further gains are feasible, but the cost of improved performance is usually a more expensive cellular infrastructure, which facilitates the reduction of the pathloss by reducing the cell size. We demonstrate in the paper how the pathloss is increased toward higher frequencies of the unlicensed 10–300-GHz band.

In contrast to the congested RF band, the optical region of the electromagnetic spectrum constitutes a tantalizingly abundant resource for telecommunications. There is an available bandwidth of hundreds of terahertz, and the low-cost light-emitting diodes (LEDs) gradually replace the obsolete incandescent bulb. The corresponding detectors can also be constructed at low cost. In the infrared (invisible) regions of the electromagnetic spectrum, research over the last several decades has led to systems operating at gigabits per second. More recently, work on visible light communications, driven by the availability of solid-state lighting sources, has led to LEDs being capable of both communicating and illuminating at the same time. There is little doubt that future wireless systems will become highly heterogeneous, with multiple standards interworking with each other, some providing very high data-rate channels in line-of-sight (LOS) scenarios, which seamlessly hand over call to indoor WiFi and outdoor cellular services to provide reliable high data-rate links. These will be complemented by low-rate, low-power standards for connecting appliances as part of the Internet of things. Hence, optical wireless may be expected to play a role in this rich spectral landscape to alleviate the teletraffic load imposed on networks with the aid of licence-free networking through the lighting system. Optical devices are natural "beamformers," and considering the signal processing complexity used in RF to realize beamforming, optical cellular systems might hold the promise of lower complexity implementations. The wavelength of light makes confining the radiation straightforward, and it can be shown that optical wireless systems may offer around 1000 times greater data density per unit area than RF-based cellular systems.

For the optical wireless (OW) revolution to become a reality, numerous challenges have to be tackled, which also requires investment in researching the relative maturity of RF wireless systems. Intensity modulation (IM) simply toggles light on and off at high frequencies, which is usually detected with the aid of direct detection (DD). The basic modulation techniques applied to light sources can only handle real-valued positive signals. Strictly speaking, this means that the well-known Shannon–Hartley theorem is not applicable in the OW domain. By contrast, digital modulation techniques typically applied in the RF domain are based on complex-valued signals, and adopting these to IM/DD results in a 50% loss of transmission bandwidth. New "cleanslate" techniques are therefore required to fully understand and harness the potential of the infrared and visible OW channels. The employment of noncoherent detection techniques results in much reduced receiver sensitivity, which might be orders of magnitude lower for OW than for RF. However, the optical equivalent of the "superheterodyne" technique does exist in the world of fiber optics. Over the next few decades, it is highly likely that the adoption of RF techniques in fiber optics becomes a commercial reality, which might also be extended to the world of free-space optics and OW. The paper in this section of the Centennial Special Issue introduces the field of OW, shows some recent results in the area of visible light communication, and sets out some of the challenges for the future. It is hoped that this will stimulate ideas from the RF and optical communities, and help develop this exciting area.

III. QUANTUM-ASSISTED AND QUANTUM-BASED SOLUTIONS IN WIRELESS SYSTEMS

Back in 1965 when Gordon Moore from Intel surmised, an interesting rule of thumb occurred to him, which was later termed as Moore's law. He concluded that since the invention of the transistor the number of transistors per chip roughly doubled every 18–24 months. The processors' performance improved, since we integrate more transistors onto a given chip area. This requires ever smaller transistors, which can only be realized, if we can have ever thinner lines on a semiconductor wafer, lines that are significantly thinner than hair. If the current trend of miniaturization continues, the aforementioned lines on the wafer will depart from the well-known natural environment, obeying well-understood rules developed step by step during the evolution of the human race, and enter into a new world, where the traveler has to obey strange new rules if he/she would like to pass through this nanoworld.

The new rules are explained by quantum mechanics, and the border between these two worlds lies around 1-nm thickness. These rules are sometimes similar to their classic (i.e., macroscopic) counterparts, but sometimes they are quite strange. The quest for quantum-domain communication solutions was started with Feynman's revolutionary idea in 1985: particles such as photons or electrons might be applied to encode, process, and deliver information. During the last three decades, researchers and engineers focused on two levels of open problems.

Classic systems with improved efficiency due to the involvement of quantum algorithms form the area of quantum-assisted communications, while quantum-based communications exploits the previously unimaginable resources of quantum channels. It is important to emphasize here that quantum channels are not unimaginable strange creations, such as the duck bill (platypus, http://en.wikipedia.org/wiki/Platypus), but they may be viewed as instantiations of the well-known and widely used optical fibers or wireless links. The difference lies in the way how information is transmitted over such communications media.

Quantum-assisted wireless communications exploits the extra computing power offered by quantum-mechanics-based architectures. Grover published his quantum-domain database search algorithm to illustrate its benefits over classic solutions. This algorithm is capable of searching through unsorted databases by initiating parallel database queries and evaluating the answers. Using the resultant efficient search algorithms, numerous problems often encountered in wireless communications may be solved efficiently. For example, we might be able to efficiently determine the most suitable resource allocation, which results in the lowest level of total cochannel interference across the entire network by simply finding the best choice of the time slots dedicated to the uplink and downlink.

Let us now turn our attention to the realms of opportunities opened up by communications over quantum channels, such as their increased capacity potential. Classically, the mutual information between the channel's input and output has to be maximized. Naturally, in case of quantum channels, the capacity had to be redefined, potentially leading to diverse scenarios to be considered. A natural distinction concerning the channel capacity definition is whether we restrict ourselves to classic bits as the system's inputs/outputs. In the case of classic inputs/outputs, we encode input symbols/states into quantum states, send them over the channel and carry out a decision at the receiver side, effectively constructing a "classic–quantum–classic" processing chain. This is a natural approach, since humans can only process classic information. By contrast, if we do not restrict ourselves to classic inputs/outputs, we are capable of dealing with quantum channels within larger quantum systems. The most important question arising in this context is whether quantum channels are capable at all of increasing the achievable capacity, and if so, under what conditions. The answer is definitively yes. Moreover, as a stunning result, redundancy-free error correction is possible over noisy transmission media, at least for a specific subset of quantum channels. And the science fiction saga still continues.

One of the hot research topics in this field is referred to as superactivation of quantum channels. Naturally, there are numerous quantum channels, which have zero capacity in the context of classic information transmission. But stunningly, when considering two of these zero-capacity channels used in a parallel manner, and additionally applying a special decoder operating by obeying the quantum-domain rules, the output of the decoder starts to deliver information.

From an implementational perspective, the most promising, but rather specific, application of quantum channels is constituted by secret quantum key distribution techniques conceived for exchanging the classic encryption keys, which can be used for symmetric-key cryptography between distant locations. Such solutions are already available for point–point links on the market, heralding a fascinating era for communications researchers. ■

ABOUT THE AUTHORS

Lajos Hanzo (Fellow, IEEE) received the M.S. degree, the Ph.D. degree, and the Honorary Doctorate "Doctor Honaris Causa" degree, all from the Technical University of Budapest, Budapest, Hungary, in 1976, 1983, and 2009, respectively.

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Dr. Hanzo is a Governor of the IEEE Vehicular Technology Society and a Fellow of the Royal Academy of Engineering, Institution of Engineering and Technology, and the European Association for Signal Processing. Since 2008, he has been the Editor-in-Chief of the IEEE Press. He coauthored 20 John Wiley/IEEE Press books on mobile radio communications totaling more than 10 000 pages, published more than 1200 research entries on IEEE Xplore, acted as both Technical Program Chair and General Chair of IEEE conferences, and presented keynote lectures. He has received a number of distinctions.

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His research interests are in quantum channel capacities, quantum computation and communication, quantum cryptography, and quantum information theory. Currently, he is completing a book on advanced quantum communications, and he teaches courses in quantum computation.

Mr. Gyongyosi received the 2009 Future Computing Best Paper Award on quantum information. In 2010, he was awarded the Best Paper Prize of University of Harvard, Cambridge, MA. In 2010, he obtained a Ph.D. Grant Award from University of Arizona, Tuscon. In 2011, he received the Ph.D. Candidate Scholarship at the BUTE; the Ph.D. Grant Award of Stanford University, Stanford, CA; the award of University of Southern California, Los Angeles; and the Ph.D. Grant Award of Quantum Information Processing 2012 (QIP2012), University of Montreal, Montreal, QC, Canada.