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Guest Editorial

Beyond Shannon Communications—A Paradigm Shift to Catalyze 6G

Angeliki Alexiou¹, *Member, IEEE*, Merouane Debbah, *Fellow, IEEE*, Marco Di Renzo², *Fellow, IEEE*, Emilio Calvanese Strinati³, *Member, IEEE*, and Harish Viswanathan⁴, *Fellow, IEEE*

I. INTRODUCTION

TARGETING ultra-reliable and scalable connectivity of extremely high data rates, in the 100 Gbps to Tbps range, at almost “zero-latency” in 6G systems would require taking advantage of breakthrough novel technology concepts, including THz wireless links, broadband and spectrally efficient RF-frontends for a variety of different bands, the employment of intelligent materials (e.g., reconfigurable intelligent surfaces) and the design of machine learning-based models, protocols, and management techniques. To materialize the 6G vision, novel system techniques will need to be devised, including channel modeling and estimation, waveforms, beamforming, and multiple-access schemes, all tailored to the particularities of the adopted breakthrough technologies. As challenging Tbit/s usage scenarios are becoming ever more relevant for 6G systems, including non-line of sight connectivity based on intelligent surfaces and ad hoc connectivity in fast-moving network topologies, e.g., based on drones or V2X links, performance targets need to be reassessed. In such scenarios, apart from the high data rates in the order of Tbit/s other critical parameters may arise as more relevant: range, reliability, adaptability, reconfigurability, and agility, to name just a few.

Together with extraordinary promises, 6G communications bring unique and novel challenges that require rethinking classical communications and networking mechanisms. The

root cause for these challenges is the multiplicity of critical performance metrics to be addressed under several newly faced particularities, such as extremely high bandwidth, extreme path loss, and severe blockage probability due to high-frequency propagation properties, highly directional links, etc. In addition, new design tools at our disposal, i.e., artificial intelligence and other machine learning techniques, motivate revisiting the layered design approach that has historically served as the mainstream method for tackling complex problems.

An interesting common characteristic of all promising 6G technology enablers under investigation is that they attempt to introduce native artificial intelligence as an integral part of the wireless system design. This intelligence is mainly associated with the capabilities of: 1) reconfiguring the design of a wireless architecture to stochastically varying conditions and/or counteracting and equalizing disruptive phenomena, such as blockage and misalignment; 2) obtaining situational, context and data content awareness; and 3) data-driven learning-based optimization of transmit, receive functionalities, as well as system optimization. Thus, by jointly optimizing the transmitter, the receiver, and the wireless environment, by means of programmable intelligent materials, the performance of wireless networks may further exceed the limits predicted by the Shannon theory for the conventional case. Moreover, focusing on semantic and goal-oriented aspects, which help the receiver identify the relevant information, i.e., the information necessary to recover the meaning intended by the transmitter, spectral efficiency goes beyond the common Shannon paradigm of guaranteeing the correct reception of each single transmitted bit, irrespective of the meaning conveyed. Other examples include the predictive learning-based optimization of the communication link through the use of a rich digital twin representation of the physical world that is expected to be available in the 6G era through, for example, the use of cameras and other data.

This Special Issue is aimed at exploring the performance merits and feasibility challenges of promising 6G enablers under the prism of advancing beyond the classical Shannon system model paradigm toward engineering the wireless environment and incorporating semantic and data-driven inference. All 63 submissions received demonstrated the timeliness and importance of research on Beyond Shannon Communications, key enablers, and challenges. After a rigorous and selec-

¹ Angeliki Alexiou is with the Department of Digital Systems, University of Piraeus, 18534 Piraeus, Greece (e-mail: alexiou@unipi.gr).

² Merouane Debbah is with the Department of Electrical Engineering and Computer Science, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates (e-mail: merouane.debbah@ku.ac.ae).

³ Marco Di Renzo is with Université Paris-Saclay, CNRS, CentraleSupélec, Laboratoire des Signaux et Systèmes, 91192 Gif-sur-Yvette, France (e-mail: marco.di-renzo@universite-paris-saclay.fr).

⁴ Emilio Calvanese Strinati is with CEA-Leti, Université Grenoble Alpes, 38400 Saint-Martin-d'Hères, France (e-mail: emilio.calvanese-strinati@cea.fr).

Harish Viswanathan is with Nokia Bell Labs, Murray Hill, NJ 07974 USA (e-mail: harish.viswanathan@nokia-bell-labs.com).

tive two-round peer-review process, 26 high-quality papers were accepted, which are briefly presented in the following section.

II. BEYOND SHANNON COMMUNICATIONS

A. Reconfigurable Intelligent Surfaces

The fundamental properties and critical characteristics of Reconfigurable Intelligent Surfaces (RIS) as a means to achieve wireless environment tunability are first discussed. The normalized array gain as well as the beam split effect in a wideband THz RIS communication system is investigated in [A1] under different RIS sizes, shapes, and deployments. It is shown that the beam squint effect with a square RIS is smaller than that with a rectangular RIS under given conditions. The same holds for a distributed RIS deployment compared to a centralized RIS deployment. To cooperatively mitigate the beam split effect by jointly designing hybrid analog/digital beamforming, time delays at the BS and RIS reflection coefficients, a time delay phase shifter for hybrid beamforming architecture is introduced. The results of [A2] show the channel hardening property in RIS-aided systems and illustrate that it is easily achieved with small transmit and receive array antennas. More interestingly, the phase shifts of reflecting elements are not required to be updated frequently and need only be appropriately matched with the large-scale statistics of the wireless channels. The analysis indicates that, using RIS, the key features of the massive MIMO technology can be achieved with rather small end-to-end dimensions. The employment of partition-based RIS schemes is investigated in [A3]. The proposed schemes are implemented without requiring any channel state information at the transmitter. The RIS elements are partitioned into sub-surfaces, which are periodically modified in an efficient way to assist communication. Two low-complexity partition schemes are proposed: 1) the activate-reflect scheme activates each sub-surface consecutively, by changing the reflection amplitude of the corresponding elements, and 2) the flip-reflect scheme adjusts periodically the phase shift of the elements at each sub-surface. Through the sequential reconfiguration of each sub-surface, an equivalent parallel channel in the time domain is produced. The performance of each scheme is analyzed in terms of outage probability and diversity-multiplexing tradeoff.

Continuous aperture MIMO and Reconfigurable Holographic Surfaces have been recently investigated as a means to achieve substantial capacity improvements while introducing tunability of the wireless environment. In [A4], a pattern-division multiplexing (PDM) scheme is proposed for Continuous-Aperture MIMO (CAP-MIMO). A typical multi-user CAP-MIMO system is formulated as a sum-rate maximization problem. A PDM technique to transform the design of the continuous pattern functions to the design of their projection lengths on finite orthogonal bases is proposed. Moreover, a block coordinate descent-based pattern design scheme is devised to solve the formulated sum-rate maximization problem. In [A5], a new paradigm of holographic radio is considered integrating numerous antenna elements into a compact space and achieving spatially quasi-continuous aperture

and high beam pattern gain. The implementation of holographic radio by a novel reconfigurable holographic surface (RHS) is capable of holographic beamforming over spatially quasi-continuous apertures, by means of densely packed tunable metamaterial elements with low power consumption. An optimization algorithm is developed for beam pattern gain maximization based on full-wave analysis of RHSs. To maximize spatial gains while performing precoding directly in the EM regime, a novel Stacked Intelligent Metasurfaces (SIM)-aided Holographic MIMO (HMIMO) design is proposed in [A6]. A channel fitting problem to approximate the expected diagonal channel matrix by optimizing the phase shifts of both the transmit and the receive side is formulated, followed by an efficient gradient descent algorithm for iteratively solving the non-trivial fitting problem. The HMIMO channel capacity is assessed and fundamental capacity scaling laws are derived.

In [A7], a multi-timescale channel customization for RIS-assisted MIMO systems is proposed, including a high-rank channel customized for spatial multiplexing (SM) transmission and a highly correlated rank-1 channel intended for beamforming (BF) transmission. The phase shifters of the RIS are designed based on statistical channel state information in the angle-coherent time to improve spectral efficiency. Closed-form expressions derived for the ergodic spectral efficiency and extensive numerical results demonstrate that flexible customization of channel characteristics can achieve an optimal trade-off between spectral efficiency and bit error ratio performance.

In the case of tightly-coupled massive MIMO systems studied in [A8] in terms of the number of antennas and the operational bandwidth, the mutual coupling is shown to widen the operational bandwidth of antenna arrays thereby unleashing a missing MIMO gain, called the “bandwidth gain.” The asymptotic analysis of the optimal spacing-to-antenna-size ratio and the assessment of the impact of the mutual coupling under line-of-sight and Rayleigh fading channels reveal new insights into the design of tightly coupled massive antenna arrays as opposed to the widely adopted designs that disregard mutual coupling.

The multi-user RIS-aided MIMO systems case is also investigated. In [A9], a practical spatially correlated RIS-aided Cell Free massive MIMO system is considered with multi-antenna access points over spatially correlated fading channels, taking into account the electromagnetic interference (EMI) at RIS. A closed-form expression is derived for the system’s spectral efficiency. Moreover, to counteract the near-far effect and EMI, practical fractional- and max-min power control algorithms are proposed. The results show that the EMI can substantially degrade the spectral efficiency and that increasing the number of RIS elements is always beneficial but with diminishing returns. Furthermore, the existence of spatial correlations among RIS elements can deteriorate the system performance when RIS is impaired by EMI.

A multi-sector beyond diagonal (BD) RIS model is formulated in [A10], which consists of multiple antennas connected to a multi-port group-connected reconfigurable impedance network. Different from the concept of simultaneously transmitting and reflecting RIS, the multi-sector BD-RIS achieves

full-space coverage and significant performance gains thanks to the highly directional beam of each sector. The scaling law of the received signal power for a multi-sector BD-RIS-assisted system is derived and efficient beamforming algorithms are designed aiming to maximize the sum-rate while striking the right balance between the number of antennas, number of sectors, and codebook resolution.

For the uplink of a RIS-assisted communication system the joint optimization of the BF vectors, power allocation, and the phase shifts at the RIS elements is studied in [A11]. A simple projected gradient descent-based optimization strategy is proposed to identify the optimal phase shift vector at the RIS elements that maximize the minimum SINR subject to power constraints. The proposed solution depends only on the asymptotic channel statistics and hence needs to be updated only according to the large-scale channel statistics.

The employment of RIS in three critical 6G usage scenarios, namely, vehicle platoons, multihop beam routing, and non-terrestrial connectivity, is also investigated. RIS-aided vehicle platoons functioning in tandem with a base station in support of high-precision location tracking are investigated in [A12]. The resultant group sparsity significantly enriches the energies of the original direct-only channel, enabling a greater concentration of the LoS channel energies to emanate from the same vehicle location index. A diverse dynamic layered structured sparsity framework is established and the location tracking problem is formulated as a maximum posterior estimate. To overcome intractability, an efficient algorithm is proposed, which incorporates both variational Bayesian inference and message-passing techniques in a turbo-like way.

In [A13], a new multi-active multi-passive (MAMP) RIS-aided wireless communication system is proposed, where a number of active and passive RISs are deployed to assist the communication between a base station and a remote user by establishing a multi-hop reflection path across active and passive RISs. An optimization problem is formulated to maximize the achievable rate of a typical user by designing the active-and-passive RIS routing path as well as the joint beamforming of the base station and selected active/passive RISs. The beam routing optimization problem is shown to be solved by a new two-phase approach. First, the inner passive-RIS beam routing between every two active RISs for effective channel power gain maximization is optimized, followed by an outer active-RIS beam routing optimization for rate maximization.

A multi-RIS cognitive satellite and terrestrial network is considered in [A14] as a promising technology to provide ubiquitous connectivity within wide coverage. The satellite network adopts multigroup multicast transmission to serve many earth stations, while the terrestrial network exploits space division multiple access and multi-RIS-enhanced non-orthogonal multiple access technology to communicate with many terrestrial users. By assuming that these two networks share the same frequency band, having only the angular information-based imperfect channel state information of each user, an optimization problem is formulated to minimize the total transmit power, subject to quality-of-service

constraints, per-antenna transmit power budget limitations, and unit-modulus requirement for each reflecting element.

Finally, antenna design and RIS hardware issues in the sub-THz regime are analyzed in [A15]. Scaling up antenna design toward the sub-THz regime and integrating unit elements into arrays might require careful consideration of co-design, packaging, scalability, and power consumption aspects. Conventional loss mitigation methods may not be sufficient and precision in fabrication may prove crucial to avoid the generation of unwanted/multimode radiations and reflections. In this paper, key hardware aspects are explained with respect to antennas and RIS, and various technological solutions are compared in order to understand their possibilities and limitations and identify promising design trends that are expected to shape 6G.

B. Semantic Communications

In the second part of this Special Issue, the potential gains and attributes of Semantic Communications are discussed. First, a novel inverse semantic communications paradigm is presented in [A16]. Instead of extracting semantic information from messages, the task-related source messages are encoded into a hyper-source message for data transmission or storage. Following this paradigm, an inverse semantic-aware wireless sensing framework is proposed with three algorithms for data sampling, RIS-aided encoding, and self-supervised decoding. To this end, a novel RIS hardware design is introduced for encoding several signal spectrums into one MetaSpectrum. A self-supervised learning method is also proposed for decoding the MetaSpectrums to obtain the original signal spectrums. Using sensing data from real-world experiments, the proposed approach can dramatically reduce the data volume compared to that before encoding, without affecting the performance of sensing tasks.

Semantics-aided communications concepts are then presented, first in a semantics-empowered two-user uplink non-orthogonal multiple access (NOMA) framework [A17]. Aiming at efficient resource utilization, a secondary far user employs the semantic communication approach (SemCom), while a primary near user employs the conventional bit-based communication (BitCom). It is shown that, compared to BitCom, SemCom can significantly improve the far user's performance under certain transmit power constraints, but may perform worse otherwise. The proposed semantics-empowered NOMA framework is investigated over fading channels. An opportunistic scheme is proposed, which enables the secondary (far) user to participate in NOMA via the most suitable communication method at each fading state, thus striking a good trade-off between its own achieved performance and the interference imposed on the primary (near) user.

The tradeoff between the informativeness of the encoded representation and the robustness against channel variation in task-oriented communications is investigated in [A18]. To analytically describe this tradeoff, the theoretical framework of robust information bottleneck (RIB) is proposed. The robustness of the communication systems is enhanced by utilizing the coded redundancy. To tackle the computation intractability

of the mutual information, a variational upper bound of the objective function is adopted. Furthermore, a task-oriented communication scheme with digital modulation is proposed, where informative messages for inference tasks are encoded into discrete representations.

In [A19], the authors study the physical-layer adversarial robustness of deep learning-based semantic communication systems under computation and energy efficiency constraints for practical deployments in real-world scenarios. A novel physical adversarial attacker is proposed that can craft semantic adversarial perturbations over wireless channels. The distortions generated are semantic-oriented and controllable, and thus, better reflecting real-world effects. Adversarial training is conducted to enhance the system's robustness against semantic attacks. Experiments show the effectiveness of the proposed approach in terms of classification accuracy, peak signal-to-noise ratio, and structural similarity index measure.

An important aspect of semantic communications is the use of adaptive semantics-based data transmission as a means to reduce the required transmission rate while improving perceptual quality. In [A20], an online learned end-to-end data transmission paradigm is proposed leveraging the deep learning model's overfitting property. An adaptive nonlinear transform source-channel coding (NTSCC) system can offer substantial gains on the end-to-end rate-distortion performance. The system design is formulated as a joint optimization problem aiming to minimize the loss function, a tripartite trade-off among the data stream bandwidth cost, the model stream bandwidth cost, and the end-to-end distortion.

An adaptive information bottleneck-guided joint source and channel coding method is proposed in [A21] for image transmission, aiming to reduce the required transmission rate while minimizing distortion and improving the image reconstruction quality. A mathematically tractable lower bound is derived and adopted as a loss function. To tradeoff compression and reconstruction quality, an adaptive algorithm is devised to adjust the parameters of the proposed loss function dynamically, according to the distortion during the training.

In [A22], two Deep Learning-based joint source-channel coding (JSCC) schemes are proposed that incorporate deep generative models to improve the perceptual quality of reconstructed images. Both approaches tackle edge cases, such as low bandwidth and low channel SNR, in which the conventional schemes typically result in poor perceptual quality. The first proposed scheme takes a novel inverse problem approach to the wireless image transmission problem, by recovering the source image with the help of a StyleGAN-2 generator. It maximizes the semantic similarity between the input and the generated images and performs well when there is a mismatch between the image distributions in training and inference times. The second Generative JSCC proposed approach, by employing an end-to-end scheme consisting of an encoder, a non-trainable channel, and a StyleGAN-based decoder, outperforms the state of the art in terms of perceptual quality metrics learned from human judgments, as well as the distortion metrics used in classical communications.

Memory is introduced into semantic communications in [A23] as a means to mimic human communications. A deep

learning-based semantic communication system with memory is investigated by considering the scenario question-answer task. A universal transformer-based transceiver is used to extract the semantic information and introduce the memory module to process the context information. Moreover, the relationship between the length of the semantic signal and the channel noise is derived to validate the possibility of dynamic transmission. Two dynamic transmission methods are proposed to enhance transmission reliability as well as to reduce communication overheads by masking some unessential elements.

In [A24], a semantic protocol model (SPM) is proposed, constructed by transforming neural network-based protocol models (NPMs) into an interpretable symbolic graph written in the probabilistic logic programming language (ProbLog). This transformation is viable by extracting and merging common control signaling messages (CMs), while treating the NPM as a CM generator. By extensive simulations, it is shown that the SPM tightly approximates its original NPM while occupying an almost negligible amount of memory. By leveraging its interpretability and memory efficiency, several SPM-enabled applications are demonstrated, such as SPM reconfiguration for collision avoidance, comparing different SPMs by means of semantic entropy calculation, and storing multiple SPMs to cope with non-stationary environments.

In the last part of this Special Issue, two novel concepts are discussed that could play an important role in the evolution towards beyond Shannon Communications era. In [A25], the performance perspective on Identification via channels (ID) is expanded from the conventionally considered upper bound of the false-positive identification error probability to the distribution of the false-positive probabilities. Based on the distance properties of the ID codeword sets and the source-sink ID pair probability distribution, the probability of randomly selecting an ID pair that exhibits a specific false-positive probability in the identification hypothesis test is defined. Moreover, interpreting the ID operation using uncoded identities as a baseline is proposed (NC) and the proportion of ID pairs is quantified whose distances increase by an ID code compared to a NC baseline. It is observed that, in some cases, the use of sophisticated ID codes increases the expected false-positive identification probability compared to the NC baseline, thus deteriorating the system performance. Moreover, the reduction of error-prone ID pairs through sending multiple tags is analytically assessed. Conclusions point toward the importance of investigating the distance distribution of ID codes and incorporating the ID pair distributions of real ID systems.

Finally, introduced by quantum mechanics, the capability of a quantum information carrier to propagate through a quantum path, i.e., through a path such that the causal order of the constituting communications channels becomes indefinite, could offer a new promising research direction. Quantum paths exhibit astonishing features, such as providing non-null capacity even when no information can be sent through any classical path. In [A26], the quantum capacity achievable via a quantum path is investigated and upper and lower bounds are derived. Results reveal the substantial advantage of a




3 levels of Communications Problems (C.E. Shannon, W. Weaver, 1964)	Enablers to advance beyond	Beyond Shannon attributes to catalyze 6G
LEVEL A. How accurately can the symbols of communications be transmitted? The technical problem		<ul style="list-style-type: none"> Wireless environment tunability/programmability Wireless environment mapping/sensing
LEVEL B. How precisely do the transmitted symbols convey the desired meaning? The semantic problem		<ul style="list-style-type: none"> Wireless connectivity beyond TX bits Semantics-aided comms
LEVEL C. How effectively does the received meaning affect conduct in the desired way? The effectiveness problem		<ul style="list-style-type: none"> Learning-based modelling, design and optimization Learning-based inference/control/prediction

Fig. 1. Beyond Shannon Communications enablers and attributes.

quantum path over any classical placements of communications channels. Furthermore, the region is identified where a quantum path incontrovertibly outperforms the amount of transmissible information beyond the limits of conventional quantum Shannon's theory.

III. CONCLUDING REMARKS

In this SI, a number of diverse beyond Shannon concepts have been introduced, analyzed, and assessed. These new intelligence features are often characterized as "beyond Shannon" communications technologies, simply because novel functionalities that are not at all considered in the classical Shannon system model, such as tunability, semantic inference, content/meaning awareness, and learning, are introduced as an integral part of the system concept. The contributions presented in this SI by no means cover all the various angles, principles, or directions of beyond Shannon communications. They, nevertheless, provide a representative sample of the technological innovation concepts that would advance communications beyond the Shannon paradigm and are expected to catalyze the 6G evolution as illustrated in Fig. 1. Shannon and Weaver in [1] explain the three different types of communication problems: the technical, semantic, and effectiveness problems, placing the emphasis on the accurate transmission of bits to the capability of conveying the content/ message of the data and to the ability to do this in a way that maximizes the effectiveness on the receiver side. Reconfigurable intelligent surfaces, semantic communications, and machine learning for communications are powerful enablers that have the potential to advance communications beyond the three levels identified 60 years ago toward programmability, situational and context awareness, semantics-aided and context-aware connectivity, and learning-based control and prediction.

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APPENDIX: RELATED ARTICLES

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Angeliki Alexiou (Member, IEEE) received the Diploma degree in electrical and computer engineering from the National Technical University of Athens in 1994 and the Ph.D. degree in electrical engineering from the Imperial College of Science, Technology and Medicine, University of London, in 2000. Since May 2009, she has been a Faculty Member with the Department of Digital Systems, where she conducts research and teaches undergraduate and postgraduate courses in broadband communications and advanced wireless technologies.

Prior to this appointment, she was with Bell Laboratories, Wireless Research, and Lucent Technologies, (later Alcatel-Lucent, now NOKIA), Swindon, U.K., from January 1999 to April 2009. She is currently a Professor of broadband communications systems with the Department of Digital Systems, ICT School, University of Piraeus, Greece. She is also the Project Coordinator of the H2020 TERRANOVA Project and the Technical Manager of the H2020 ARIADNE Project. Her current research interests include radio interface for 6G systems, MIMO, THz wireless communication technologies, reconfigurable intelligent surfaces, cooperation and coordination for ultra-dense wireless networks, cell-less architectures, and machine learning for wireless systems. She was a co-recipient of the Bell Labs President’s Gold Award in 2002 for contributions to Bell Labs Layered Space-Time (BLAST) Project and the Central Bell Labs Teamwork Award in 2004 for role model teamwork and technical achievements in the IST FITNESS Project. She is the Chair of the Working Group on Radio Communication Technologies and the Working Group on High Frequencies Radio Technologies of the Wireless World Research Forum.



Merouane Debbah (Fellow, IEEE) received the M.Sc. and Ph.D. degrees from Ecole Normale Supérieure Paris-Saclay, France. He was with Motorola Labs, Saclay, France, from 1999 to 2002, and then with the Vienna Research Center for Telecommunications, Vienna, Austria, until 2003. From 2003 to 2007, he was an Assistant Professor with the Mobile Communications Department, Institut Eurecom, Sophia Antipolis, France. Since 2007, he has been a Full Professor with CentraleSupélec, Gif-sur-Yvette, France. From 2007 to 2014,

he was the Director of the Alcatel-Lucent Chair on Flexible Radio. From 2014 to 2021, he was the Vice-President of the Huawei France Research Center. He was jointly the Director of the Mathematical and Algorithmic Sciences Laboratory as well as the Director of the Lagrange Mathematical and Computing Research Center. From 2021 to 2023, he was the Chief Researcher with the Technology Innovation Institute and led the AI and Digital Science Research Center, Technology Innovation Institute. He was also an Adjunct Professor with the Department of Machine Learning, Mohamed bin Zayed University of Artificial Intelligence, Abu Dhabi. Since 2023, he has been a Professor with the Khalifa University of Science and Technology, Abu Dhabi, and the Founding Director of the 6G Center. He is currently a Professor with the Khalifa University of Science and Technology. He has managed eight EU projects and more than 24 national and international projects. He holds more than 40 patents. His research interests include fundamental mathematics, algorithms, statistics, information, and communication sciences research. He is a WWRF Fellow, a EURASIP Fellow, an AAIA Fellow, an Institut Louis Bachelier Fellow, and a Membre émérite SEE. He was a recipient of the ERC Grant MORE (Advanced Mathematical Tools for Complex Network Engineering) from 2012 to 2017. He received multiple prestigious distinctions, prizes, and best paper awards (more than 35 best paper awards) for his contributions to both fields and according to research.com is ranked as the best scientist in France in the field of electronics and electrical engineering.



Marco Di Renzo (Fellow, IEEE) received the Laurea (cum laude) and Ph.D. degrees in electrical engineering from the University of L’Aquila, Italy, in 2003 and 2007, respectively, and the Habilitation à Diriger des Recherches (Doctor of Science) degree from University Paris-Sud (currently Paris-Saclay University), France, in 2013. Currently, he is a CNRS Research Director (Professor) and the Head of the Intelligent Physical Communications group in the Laboratory of Signals and Systems (L2S) at Paris-Saclay University – CNRS and CentraleSupélec, Paris, France. At Paris-Saclay University, he serves as the Coordinator of the Communications and Networks Research Area of the Laboratory of Excellence DigiCosme, as a Member of the Admission and Evaluation Committee of the Ph.D. School on Information and Communication Technologies, and as a Member of the Evaluation Committee of the Graduate School in Computer Science. He is a Founding Member and the Academic Vice Chair of the Industry Specification Group (ISG) on Reconfigurable Intelligent Surfaces (RIS) within the European Telecommunications Standards Institute (ETSI), where he serves as the Rapporteur for the work item on communication models, channel models, and evaluation methodologies. He is a Fellow of the IEEE, IET, and AAIA; an Ordinary Member of the European Academy of Sciences and Arts, an Ordinary Member of the Academia Europaea; and a Highly Cited Researcher. Also, he holds the 2023 France-Nokia Chair of Excellence in ICT, and was a Fulbright Fellow at City University of New York, USA, a Nokia Foundation Visiting Professor, and a Royal Academy of Engineering Distinguished Visiting Fellow. His recent research awards include the 2021 EURASIP Best Paper Award, the 2022 IEEE COMSOC Outstanding Paper Award, the 2022 Michel Monpetit Prize conferred by the French Academy of Sciences, the 2023 EURASIP Best Paper Award, the 2023 IEEE ICC Best Paper Award (wireless), the 2023 IEEE COMSOC Fred W. Ellersick Prize, the 2023 IEEE COMSOC Heinrich Hertz Award, and the 2023 IEEE VTS James Evans Avant Garde Award. He served as the Editor-in-Chief of IEEE COMMUNICATIONS LETTERS during the period 2019-2023, and he is now serving in the Advisory Board.

At Paris-Saclay University, he serves as the Coordinator of the Communications and Networks Research Area of the Laboratory of Excellence DigiCosme, as a Member of the Admission and Evaluation Committee of the Ph.D. School on Information and Communication Technologies, and as a Member of the Evaluation Committee of the Graduate School in Computer Science. He is a Founding Member and the Academic Vice Chair of the Industry Specification Group (ISG) on Reconfigurable Intelligent Surfaces (RIS) within the European Telecommunications Standards Institute (ETSI), where he serves as the Rapporteur for the work item on communication models, channel models, and evaluation methodologies. He is a Fellow of the IEEE, IET, and AAIA; an Ordinary Member of the European Academy of Sciences and Arts, an Ordinary Member of the Academia Europaea; and a Highly Cited Researcher. Also, he holds the 2023 France-Nokia Chair of Excellence in ICT, and was a Fulbright Fellow at City University of New York, USA, a Nokia Foundation Visiting Professor, and a Royal Academy of Engineering Distinguished Visiting Fellow. His recent research awards include the 2021 EURASIP Best Paper Award, the 2022 IEEE COMSOC Outstanding Paper Award, the 2022 Michel Monpetit Prize conferred by the French Academy of Sciences, the 2023 EURASIP Best Paper Award, the 2023 IEEE ICC Best Paper Award (wireless), the 2023 IEEE COMSOC Fred W. Ellersick Prize, the 2023 IEEE COMSOC Heinrich Hertz Award, and the 2023 IEEE VTS James Evans Avant Garde Award. He served as the Editor-in-Chief of IEEE COMMUNICATIONS LETTERS during the period 2019-2023, and he is now serving in the Advisory Board.



Emilio Calvanese Strinati (Member, IEEE) received the master's degree in engineering from the University of Rome 'La Sapienza' in 2001 and the Ph.D. degree in engineering science from Paris Telecom in 2005. He was with Motorola Labs, Paris, in 2002. In 2006, he joined CEA-LETI, as a Research Engineer. Since 2007, he has been a Ph.D. Supervisor. From 2010 to 2012, he has been the Co-Chair of the Wireless Working Group, GreenTouch Initiative, which deals with the design of future energy-efficient communication networks.

From 2011 to 2016, he was the Smart Devices and Telecommunications Strategic Programs Director, and then, until January 2020, he was the Smart Devices and Telecommunications Scientific and Innovation Director. Since February 2020, he has been the Nanotechnologies and Wireless for 6G (New-6G) Program Director with a focus on future 6G technologies. He has also a rather strong and successful experience in leading and coordinating research activities having been the main coordinator of successful projects, such as 5G-CHAMPIONS, 5GAllstar, or RISE-6G. CEA has also coordinated other FP7/H2020 and national projects, and/or served regularly as the Project Technical Manager and a Work Package and Task Leader for more than 35 European projects. He has published around 200 papers in journals, international conferences, and book chapters, and he has given more than 200 international invited talks, keynotes, and tutorials. He is the main inventor of more than 80 patents. His current research interests include reconfigurable intelligent surfaces, semantic communications, and goal-oriented communications AI-native technologies in the context of future 6G networks.



Harish Viswanathan (Fellow, IEEE) received the B.Tech. degree from the Department of Electrical Engineering, Indian Institute of Technology, Chennai, India, and the M.S. and Ph.D. degrees from the School of Electrical Engineering, Cornell University, Ithaca, NY, USA. He is currently the Head of the Radio Systems Research Group, Nokia Bell Labs. Since joining Bell Labs in October 1997, he has worked extensively on wireless research ranging from the physical layer to network architecture and protocols including multiple antenna technology for cellular wireless networks, multi-hop relays, network optimization, network architecture, and IoT communications. From 2007 to 2015, he was with Corp CTO Organization, where, as a CTO Partner, he advised the Corporate CTO on technology strategy through in-depth analysis of emerging technology and market needs. He has extensively published more than 100 papers. He is a fellow of Bell Labs.