Newsletter

IEEE ComSoc Technical Committee on Cognitive Networks (TCCN)

December 2023

Contents

1. Chair’s Message

Dear TCCN Colleagues:

It is a great honor and pleasure to serve as TCCN Chair for 2023 $\in$ 2024. In the first year of our term, I enjoyed working with all the TCCN officers and members, to serve the TCCN community and to continue the past success of TCCN. Thank you all for your collaboration and support!

TCCN is the ComSoc technical committee (TC) focusing on cognitive and artificial intelligence (AI) empowered networking research, development, policy making and standardization. The technical issues addressed by the TC include spectrum agile/dynamic spectrum access networks, related issues from PHY to application layers, security and privacy issues, policy issues, implementation technologies, economic considerations and standardization activities. This is really a broad and timely scope, given the vast interest in our community on incorporating AI/ML in the next generation wired and wireless networks. TCCN is the home TC for us working in this exciting area.

I would like to take this opportunity to share several great news. As you may know, each ComSoc TC should go through a recertification process every three years. It is TCCN’s turn this year. Thanks to Dr. Hongliang Zhang (TCCN secretary) for collecting the required information and all those who provided inputs! The TC Recerfitication Committee has unanimously agreed that "TCCN is running very well" and TCCN has been successfully recertified. Our next recertification will be in 2026.

This year, the ComSoc Technical and Educational Activities Council (TEA-C) provided funding for TCs/ETIs on innovation projects and a video compaign. TCCN is among the few TCs/ETIs that are funded by both programs. Thanks to Dr. Boya Di for leading the TCCN Innovation Project! The TC Innovation Project fund allows us to host two talks on emergying new technologies at our TC meeting at IEEE GLOBECOM 2023:

1. Distributionally Robust Optimization and Machine Learning for Communication Networks
   By Dr. Zhu Han, ECE Department and CS Department, University of Houston
2. Reconfigurable Holographic Surfaces: A New Paradigm to Ultra-Massive MIMO for 6G
   By Dr. Lingyang Song, School of Electronics, Peking University, China

You are cordially invited to the in-person meeting and talks 6:00-9:00 PM, Tuesday, Dec. 5th, 2023, at Poolside Residence 302 of the Grant Hyatt, Kuala Lumpur, Malaysia. Or join our zoom meeting:

https://auburn.zoom.us/j/9172542706?pwd=YVBYekVtR3lpTGRaclpvZm11ZDV3Zz09

The TC Video Campaign fund will allow us to produce a short video to promote TCCN. Dr. Hongliang Zhang and I are working with IEEE.tv on video production. If you have any ideas and suggestions, please do not hesitate to let us know.

TCCN also organizes a webinar series on cutting-edge technologies, with four talks per year. In addition, some of our SIGs, in particular, the TCCN SIG on AI and Machine Learning in Security led by Dr. K.P. (Suba) Subbalakshmi and Dola Saha also organizes a series of webinars. All the past webinar slides/videos can be found at the TCCN Seminar website at: *https://cn.committees.comsoc.org/seminars/*

I would also like to bring to your attention of the many resources and opportunities TCCN offers to its members. Please check out the TCCN website (*https://cn.committees.comsoc.org*) for TCCN sponsored journals, conferences & workshops, newsletters, and Interest Groups. TCCN helps its members for elevation to sensior member or Fellow of the IEEE, and nominates Distinguished Lectures to ComSoc. TCCN also recognizes its members with the TCCN Recognition Awards and TCCN Publication Awards. Join me to congratulation this year's winners:

1. Dr. Rui Zhang for the TCCN Recognition Award
2. Drs. Zhu Han and Boya Di for the TCCN Publication Award.

Please stay tuned for announcements on the TCCN mailing list for various call for nominations.

There are two specific areas that we can make further improvement. First, we could recruit more members, given that machine learning and spectrum related research are becoming mainstream of ComSoc. The streamlined membership subscription website is: *https://cn.committees.comsoc.org/voting-members/*. Anyone who is working on related fields can enter his/her name and email address to become a TCCN member. Note that no IEEE or ComSoc membership is required. Please spread the words and encourage your friends, colleages, and more important, your students to subscribe. I am sure your students will greatly benefit from participation in TCCN events, as I have over the years.

Second, we need to have more submissions to the Cognitive Radio and AI-Enabled Networks (CRAEN) Symposium at IEEE ICC and GLOBECOM. This is a symposium primarily sponsored by TCCN, and we recommend our members to serve as symposium co-chairs. In recent years this symposium is facing direct competition with the SAC on Machine Learning for Communicaitons. Please kindly consider submitting your work to the ICC/GC CRAEN

Symposium.

Kudos to our Newsletter Director Dr. Dola Saha! I hope you enjoy reading this issue of TCCN newsletter, and strongly encourage you to get more involved in TCCN. If you have any suggestions or comments, please do not hesitate to contact me.

Sincerely,

Shiwen Mao,
Chair, IEEE ComSoc Technical Committee on Cognitive Networks (TCCN)
Professor and Earle C. Williams Eminent Scholar, Fellow of the IEEE
Director, Wireless Engineering Research and Education Center
Dept. of Electrical & Computer Engineering
Auburn University
200 Broun Hall
Auburn, AL 36849-5201
Email: *smao@ieee.org*
URL: *http://www.eng.auburn.edu/users/szm0001*

Bio: SHIWEN MAO is a professor and Earle C. Williams Eminent Scholar Chair, and Director of the Wireless Engineering Research and Education Center (WEREC) at Auburn University, Auburn, AL, USA. His research interests include wireless networks, multimedia communications, and smart grid. He is a Distinguished Lecturer of IEEE Communications Society and the IEEE Council of RFID, and is the Editor-in-Chief of IEEE Transactions on Cognitive Communications and Networking. He received the IEEE ComSoc MMTC Outstanding Researcher Award in 2023, IEEE ComSoc TC-CSR Distinguished Technical Achievement Award in 2019, and NSF CAREER Award in 2010. He is a co-recipient of the 2022 Best Journal Paper Award of IEEE ComSoc eHealth TC, the 2021 Best Paper Award of Elsevier/KeAi Digital Communications and Networks Journal, the 2021 IEEE Internet of Things Journal Best Paper Award, the 2021 IEEE Communications Society Outstanding Paper Award, the IEEE Vehicular Technology Society 2020 Jack Neubauer Memorial Award, the 2018 Best Journal Paper Award and the 2017 Best Conference Paper Award from IEEE ComSoc MMTC, the 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems, and several ComSoc service and conference best paper/demo awards. He is a Fellow of the IEEE.

2. Newsletter Director's Note

Dear Fellow TCCN Members:

It is my extreme honor and great pleasure to introduce the newsletter that highlights recent progress in cognitive communication as well as thought-provoking new avenues of future research and challenges in the field from world class leaders.

We have come across a long way since Marconi first demonstrated wireless communication in 1894. Over a century later, we are still working on wireless communication to support high bandwidth low latency emerging applications, like virtual reality, telesurgery, 3D holographic communication, etc. and ubiquitous connectivity for exponentially growing number of devices. To support the demand arising from all these scenarios, it is essential to critically rethink the communication systems to not only make the radios to be cognitive, but the end-to-end links and networks to be smart, autonomous and capable of reasoning for a resilient system. Cognitive communication is undergoing a major shift in paradigm from only classical signal processing based methods to various data driven approaches that have been shown to perform better than prior methods. However, due to the black-box nature of learning based methods and high dependency on training data set, practical adoption is still sparse specially in critical applications. This is precisely where the data driven learning models can be improved with physics based domain knowledge that can make the systems explainable, predictable, adaptable and enhanced with causal reasoning. The future of cognitive communication lies in the confluence of signal processing and machine learning based approaches, reaping the benefits of both the domains towards a lifelong learning without catastrophic forgetting.

In this newsletter, we have two visionary articles, one from Dr. Tim O'Shea and the other from Prof. Gunes Karabulut Kurt. Dr. O'Shea's article shows various pathways for scalable systems using data driven models. Prof. Kurt's article delves into the topic of cognition in space communication, which is getting crowded at an extremely fast pace. We have also interviewed five renowned scholars, Prof. Ying-Chang Liang, Prof. Sofie Pollin, Prof. Bhaskar Krishnamachari, Dr. Nada Golmie and Prof. Josep Jornet. They have all shared their insights for future cognitive communication systems and the challenges ahead of us in tackling those topics.

I would like to sincerely thank all the contributors for taking the time to share their thoughts with the readers of the TCCN newsletter in their busy schedule. I hope all of you will cherish reading the articles and interviews as I did.

Sincerely,

Dola Saha
Director, IEEE ComSoc TCCN Newsletter
Associate Professor
Department of Electrical & Computer Engineering
University at Albany, SUNY
Email: *dsaha@albany.edu*
URL: *https://www.albany.edu/faculty/dsaha/*

Dola Saha is an Associate Professor in the Department of Electrical & Computer Engineering at University at Albany, SUNY. She co-directs the Mobile Emerging Systems and Applications (MESA) Lab at UAlbany. She was a faculty fellow at Jet Propulsion Laboratory, Caltech, NASA in summer of 2022. She was a visiting faculty at the Air Force Research Laboratory in summers of 2020 and 2021. She is the Vice Chair of the IEEE ComSoc TCCN SIG for AI and Machine Learning in Security and has been appointed a member of the SUNY Innovations Policy Board. Prior to that, she was a Research Assistant Professor in the Department of Electrical & Computer Engineering at Rutgers University. Before that, she was a Researcher in the Mobile Communications and Networking group at NEC Laboratories America. She received Best Paper Award in DySPAN 2015 and 2021. She received her Masters and Doctorate degrees from the Department of Computer Science in the University of Colorado Boulder. She is the recipient of Google Anita Borg Scholarship for her academic credentials. Her research interests lie in the crossroads of Machine Learning for Wireless Communication, Wireless Security, Wireless Signal Processing, and Architectures of Software Defined Radios with focus on systems design and practical evaluation.

3. Visions of Dr. Tim O'Shea

Data is Accelerating Communications Technology

Author: Dr. Tim O'Shea,
CTO DeepSig Inc.,
Research Assistant Professor, Virginia Tech,
Arlington, VA, USA, USA,
Email: *tim@deepsig.ai*

COMMUNICATIONS technology is accelerating from the recent advances in data-driven optimization using AI/ML which have been broadly impacting language, vision, speech, goal-seeking, and software more broadly. Deep learning has broadly and fundamentally effected these fields by allowing for much more abstract end-objective based design which can be learned through ever more complex tasks, architectures, and scales of datasets, and it is doing the same for communications systems within our field. Cognitive Communications and Cognitive Radio have been investigated within the communications community and TCCN for many years, yet they have often struggled for the same reason as AI-more-broadly gaining widespread adoption throughout the second "AI Winter." These struggles were often around, how do we scale, implement, and generalize the broad ideas of intelligence within communications systems? We knew we wanted intellegent systems, but the path to realizing them was not clear. Today it is clearer than it has ever been, and we are beginning to see broad adoption come to reality. We'll highlight a few of the key ideas we see as the enablers here, highlight some of our own recent work in the area as well

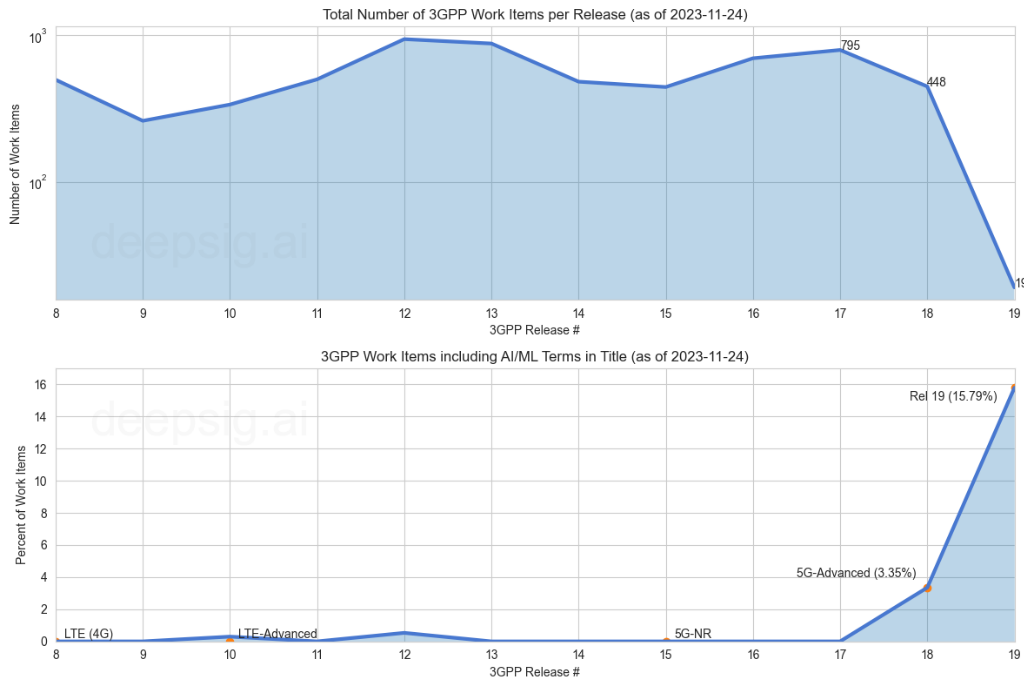


Figure 3.1: 3GPP Work Items

as other key contributions from the field, and speculate as to where we are headed.

3.1 Introduction

Communication technology, and its entire design and deployment process has been heavily disrupted, and is accelerating more than we have seen in recent time. By leveraging end-to-end learning and data-driven gradient descent throughout the design and implementation for communications signal protocols, processing and controls which drive it [OH17], we are seeing greater change and disruption to communications systems than we have for some time, especially at the lower layers of the stack. To highlight some of these, we will survey a handful of areas effecting and effected by these changes which directly relate to the area of intelligent or cognitive communications systems.

3.2 AI-Native Modems in 6G and Next Generation Standards

6G presents a unique opportunity to make significant changes to the physical layer standards used broadly within our mobile computing devices. As such, there have been quite a number of discussions around, if we can move to an AI-Native Air-Interface, a pilot-free communications scheme [AH22], or even to a Semantic Communications scheme which combines source and channel coding to be more efficient for end-applications [BBG19]. Each of these adds significant spectral efficiency in terms of end-user-applications to the technologies deployed in 5G today. On top of this, numerous suggestion have been made

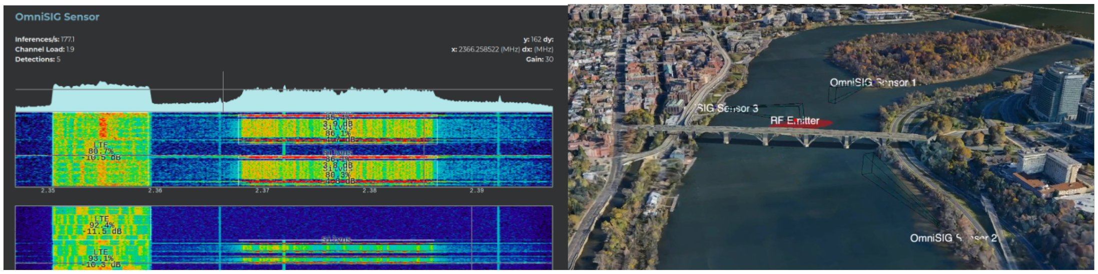


Figure 3.2: Deep Learning data-driven neural inference for Signal Detection, Identification, and Localization with DeepSig's OmniSIG Software

for expansions on current day forward error correction (FEC) techniques using end-to-end learning [Gei+23] as well as adoption within 5G Advanced for various functions such as neural receivers and ML-driven channel state information (CSI) feedback [Lin22], and adoption of Massive MIMO (mMIMO) techniques into more distributed (dMIMO) and sometimes non-orthogonal multiple access (NOMA) schemes [Sen+19].

Figure 3.1 illustrates the growth of these AI/ML driven ideas into 3GPP standardization for next generation cellular systems, by highlighting simply occurrences within work/study item names. While we have seen a rapid growth in AI/ML focus within these work study items, it is interesting to note where they have been adopted and within which time-frame. Rel-18 is the earliest major adopter, reflecting the first iteration of 5G Advanced, but with only very limited adoption of AI/ML, within limited changes to existing systems, primarily within very limited functions, while later release of 5G Advanced and 6G (release 20/21) will look at deeper ways at which these can be integrated.

3.3 Real-Time AI-Native Spectrum Sensing, Identification, and Spatial Awareness

Spectrum is an increasingly dense, dynamic and scarce resource. For this reason, as well as for security and reliability purposes, real-time awareness of spectrum utilization is critical not only to controlling our spectrum access, but to enabling optimization of multi-user, multi-sector, multi-network, and multi-technology spectrum orchestration. Spectrum sensing/awareness as a data-driven task is a relatively new approach which has traditionally been performed using purely model-driven methods. Many of the breakthroughs which were made in computer vision for object detection, classification, segmentation, tracking and otherwise can be combined with radio domain knowledge and processing to provide an order of magnitude improvement in speed, sensitivity, accuracy, and rate of development. This has been a core focus at DeepSig over the last 7 seven years in hardening software to bring this to production, and has been an area of investigation for many researchers worldwide as in recent years as well.

More recently, we've spent time expanding these ML-driven spectral awareness methods for real-time spectrum monitoring to incorporate a spatial dimension, providing rapid localization from one or more sensors into a real time emitter spectral and spatial monitoring platform, as shown in figure 3.2, which illustrates both the spectral detection and classification of emissions and their per-emission localization. Bringing sensing and local-

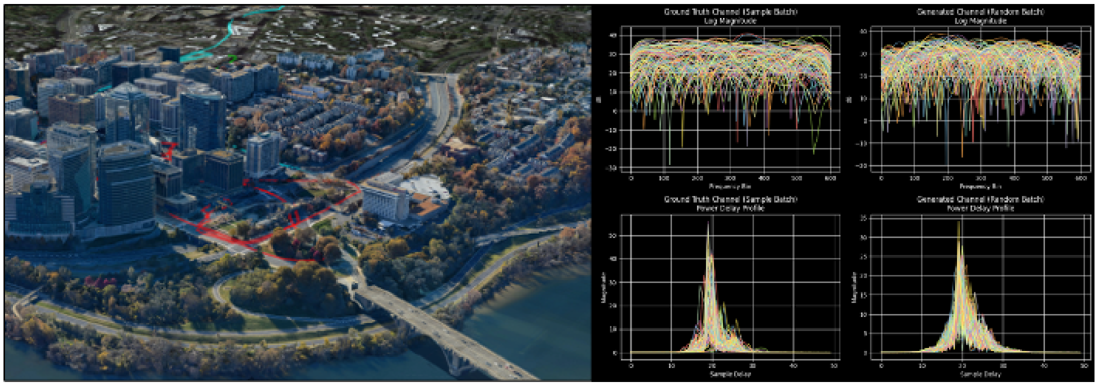


Figure 3.3: Data-driven "Digital Twin" channel modeling using Deep Neural Generative AI to reflect real-world measurements, CSI, and propagation effects

ization capabilities to both scale and robustness allows for a volume and speed of spectrum awareness we haven't seen before through other means – and I believe, most importantly builds the foundation on top of which a range of intelligent wireless system behaviors can be built including spectrum sharing and adaptation, spectrum coordination between sectors and systems, broad spectrum analytics and alerting, MIMO scheduling and beam optimization, and a range of other tasks which can benefit from this raw information. To this end, we hope such information can become more universal within wireless systems as the cost of compute continues to decrease, allowing the usage of more data at lower cost.

3.4 Data Driven Channel Modeling and Continuous Local World Models

One of the greatest lessons of AI/ML driven techniques of the past decade is that the performance of learned systems is often only as good as the dataset used in training. For the design of autoencoder style communications systems which are nominally unsupervised (i.e. reconstruction loss with no labels), or otherwise data-driven components such as neural receivers, our "dataset" is often more-so the channel effects, propagation and hardware effects, interference effects, and resulting channel impulse response over which the system must operate. Training and testing ML communications systems against simplified statistical channel models such as AWGN or simplified fading models often misses the point, because it does not fully reflect the real world channel response the system will be deployed into. For this reason, locally-optimized wireless systems have begun to be a focus within the wireless community and within 6G research. Only under a locally optimized model can we often really measure or optimize for the maximum performance of a model within a specific local deployment. To enable this, we need to continue to mature data-driven capture and modeling of channel responses for many local environments in which these wireless systems must operate.

To this end, DeepSig has been incredibly fortunate to be one of the first recipients of the NTIA's Public Wireless Supply Chain Innovation Fund (PWSCI) grant, seeking to advance the performance and competitiveness of 5G OpenRAN systems. In this case, ML can do so through both measurement of air-interface performance in local wireless environments, as well as through optimization of wireless signal processing functions such as neural receivers, locally. In figure 3.3 we illustrate recent work, capturing real-time impulse response drive propagation data along with precise time and location, in order to help to capture local channel environments precisely. These may in turn be used to enable Generative-AI driven channel models which can expand and emulate accurate channel effect distributions to help both optimize and test wireless systems and OpenRAN Air Interfaces in these respective environment.

This work in data-driven channel modeling is still fairly early, stemming from earlier works on generative and variational channel models [ORW19], but it is clear that as we build the requirements for 6G wireless systems, we must move beyond broad models such as TDL and CDL models, to encompass models with better spatial consistency [Kur+19] and higher accuracy in other aspects over a range of localities and environments beyond pure Doppler and delay spread modeling, as were the primary models for 4G and 5G. Over the next two years we are excited to share updates on our generative AI driven channel progress, and will be excited to see where the rest of the research community continues to explore in this space as well.

As both 3GPP and OpenRAN standards evolve, there seems to be an increasing collective vision that this kind of data measurement for local effects and real-world locality modeling is a core function of what the RF "Digital Twin" may offer for radio access network (RAN) optimization, and spectral orchestration. It may offer many other utilities beyond this as well such as predictive mode selection, path planning, scheduling, power management, inverse localization, etc.

3.5 AI-Native Modem Optimization in Existing Standards, 5G, OpenRAN, and Private-5G Deployments

One of the most immediate applications of machine learning and deep learning within communications systems, and the physical layer, is simply that of transparently optimizing existing wireless communications systems such as 4G and 5G-NR without standards changes. These are, today, the primary carriers for all of our cellular wireless communications, and performance in 5G infrastructure. Today traditional integrated RAN vendors often have significant investment in their proprietary receivers and other algorithms to attain competitive performance in terms of sensitivity and link-margin, however as we move to an Open and Distributed RAN, such algorithms must also be competitive, if not better, to allow for ORAN/vRAN solutions to attain similar spectral efficiency and value to operators. This is an area of focus as well where we have tried to help close the performance gap by providing improved and competitive software components.

In figure 3.4 we highlight one such examples where a neural receiver for 5G PUSCH uplink can out-perform many existing baseline receiver algorithms, and can also be easily deployed along Intel's FlexRAN L1 receiver stack. We highlight integration of OmniPHY with HTC G-REIGNS' private 5G system here, but results are broadly applicable to many 5G systems. By increasing sensitivity, numerous benefits can be realized in vRAN such as increased cell coverage, throughput, spectral efficiency, etc. Through careful design of the neural receiver and the use of neural network specific silicon such as Intel's Deep Learning

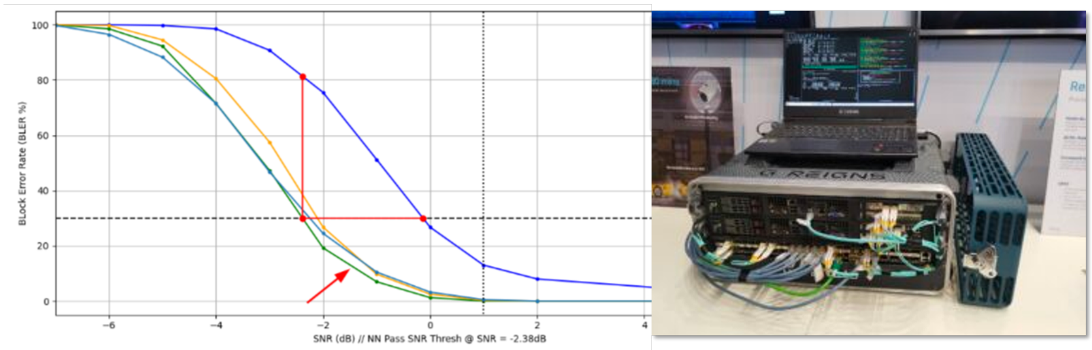


Figure 3.4: OmniPHY-5G Impact of MIMO 5G-NR OpenRAN for a 2x4 System Uplink Margin using AI-Native Receiver alongside HTC P5G System Partner

Boost (DLBoost) instructions, such a receiver can run without increasing computational load, and in some cases decreasing it within the DU.

While this is only the first step towards AI/ML enabled vRAN/cRAN capabilities to improve performance and value to operators, we believe it helps to demonstrate the immediate value and impact ML in Comms can have to systems today even transparently and fully within existing standards. However, the future is even more broad and benefits greater further down the road when considering potential new standards.

3.6 Towards the future of communications

Each of these examples has demonstrated how AI/ML capabilities in the PHY are enabling next generation communication systems directly in terms of spectrum awareness, channel and propagation modeling, and in physical layer modem design. However, as we pull all of these together into a concept for what future communications system could look like, which takes advantage of AI/ML and data in every way possible, we can begin to predict what future smart wireless protocols might look like.

To this end, we have been building OmniPHY (end-to-end) as our proof-of-concept system for an AI-Native Communications system. From a learning perspective, using an autoencoder approach, we can now learn new modulations and/or error correction codes which attain or improve on state of the art methods in many conditions — and which can be fine tuned for specific local environments, interference models, adversarial models, or other impairments.

Figure 3.5, shows several views of one such learned autoencoder communications systems, illustrating an entire sweep of block-error rate (BLER) curves for different learned information rates across a channel, and further illustrating learned constellations for one of these rates. In this way, we can learn the full range of high and low rate PHY modes, and can adapt them to local conditions, making them widely useable today with rate adaptation and higher layer components for a complete system.

This class of data-driven PHY optimizations can have a significant impact even under benign channel conditions, where sensing and spectrum coordination, local-channel modeling

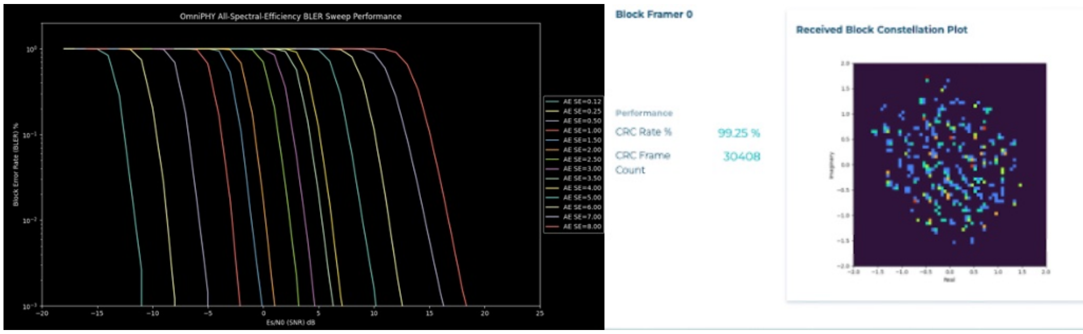


Figure 3.5: End-to-end learned PHY encoding techniques over range of information rates running over the air in real-time 20Mbps+ using DeepSig's OmniPHY

and coordination, and local receiver or end-to-end modem optimization can be performed, but the impact is even more so under adverse conditions such as hardware impairments, adversarial conditions, and where a wide range of other effects may be present. This may reveal a number of areas within hardware communications system design where we can continue to relax RF requirements, and further reduce power an cost of such systems by being able to adapt around them in future systems, and provide an enabler to operating in new environments and channels.

Hopefully this has been able to provide a bit of a window into some of the things we're still very excited about and focused on, and some of the areas we believe AI/ML in communications systems will continue to have a significant impact. It is an exciting time in communications, where nearly every function we've optimized for from a model-driven perspective can now be reconsidered from this end-to-end learning perspective, and we can really start building true cognitive communications systems, which achieve numerous new performance levels and capabilities. We'll be excited to see where research in this area goes, and continue to advance our own work in the area as quickly as possible, 6G which once seemed far away seems to be becoming much more real and immediate every day.

References

[OH17] Timothy J O'Shea and Jakob Hoydis. "An Introduction to Deep Learning for the Physical Layer". In: *IEEE Transactions on Cognitive Communications and Networking* (2017).

[AH22] Fayçal Ait Aoudia and Jakob Hoydis. "End-to-End Learning for OFDM: From Neural Receivers to Pilotless Communication". In: *IEEE Transactions on Wireless Communications* 21.2 (2022), pages 1049–1063. DOI: *10.1109/TWC.2021.3101364*.

[BBG19] Eirina Bourtsoulatze, David Burth Kurka, and Deniz Gündüz. "Deep Joint Source-Channel Coding for Wireless Image Transmission". In: *IEEE Transactions on Cognitive Communications and Networking* 5.3 (2019), pages 567–579. DOI: *10.1109/TCCN.2019.2919300*.

[Gei+23] Marvin Geiselhart et al. "6G: A Welcome Chance to Unify Channel Coding?" In: *IEEE BITS the Information Theory Magazine* (2023), pages 1–12. DOI: *10.1109/MBITS.2023.3322974*.

[Lin22] Xingqin Lin. "An overview of 5G advanced evolution in 3GPP release 18". In: *IEEE Communications Standards Magazine* 6.3 (2022), pages 77–83.

[Sen+19] Kamil Senel et al. "What Role can NOMA Play in Massive MIMO?" In: *IEEE Journal of Selected Topics in Signal Processing* 13.3 (2019), pages 597–611. DOI: *10.1109/JSTSP.2019.2899252*.

[ORW19] Timothy J. O'Shea, Tamoghna Roy, and Nathan West. "Approximating the Void: Learning Stochastic Channel Models from Observation with Variational Generative Adversarial Networks". In: *2019 International Conference on Computing, Networking and Communications (ICNC)*. 2019, pages 681–686. DOI: *10.1109/ICCNC.2019.8685573*.

[Kur+19] Martin Kurras et al. "Evaluation of the spatial consistency feature in the 3GPP geometry-based stochastic channel model". In: *2019 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2019, pages 1–6.

The Author

Tim O'Shea (Senior Member) (SM'14) is the CTO and Co-Founder of DeepSig and Research Assistant Professor at Virginia Tech in Arlington, VA. Tim's focus is on rapidly transitioning machine learning communications systems to industry where they can impact 5G OpenRAN, 6G RAN, non-standards-based comms, and spectrum sensing applications and performance dramatically. Previously, he helped launch wireless startups Hawkeye 360 and Federated Wireless. Authored over 100 academic papers and patents and worked to support a number of initiatives including within IEEE ComSoc, IEEE MLC ETI, IEEE TWC, IEEE TCCN, Next-G Alliance, GNU Radio, and OpenRAN Alliance. He has served on boards and panels for NSF, DARPA, IARPA, and others.

4. Visions of Prof. Gunes Karabulut Kurt

On The Necessity of Cognitive Capabilities in New Space

Author: Prof. Gunes Karabulut Kurt,
Department of Electrical Engineering,
Polytechnique Montréal
Montreal, Canada
Email: *gunes.kurt@polymtl.ca*

The New Space paradigm, led by private companies, brought commercialization, innovation, and sustainability, influencing satellite networks, reducing launch costs, and fostering mega-constellations for global broadband Internet coverage. Mega-constellations are expected to offer direct-to-device connectivity, addressing the digital divide and enhancing disaster response. Beyond communication services, these mega-constellations can enable computational offloading and caching. However, their tight operational constraints will require seamless integration with ground infrastructure and the use of diverse frequency bands, which can be managed by cognitive radio principles. Cognitive radio in satellite networks has the potential to enhance spectrum utilization, communication reliability, and autonomy, optimizing resource allocation and supporting cross-layer interactions. Cognitive capabilities can also extend to space domain awareness (SDA), which is vital for collision prediction, safe maneuvers, and space traffic management. SDA monitors satellite positions, tracks space debris, and ensures responsible space use, contributing to a safer and sustainable space environment. Incorporating cognitive radio into SDA systems promises adaptive, efficient, and resilient communication networks, contributing to the promising future of space exploration and satellite technology in the New Space era.

4.1 Introduction

There is a new paradigm shift in the space industry, the so-called New Space. This shift is characterized by the emergence of private companies and entrepreneurial ventures in space-related activities [Eur16]. This new paradigm contrasts with the traditional space industry dominated by government agencies and large aerospace corporations with conventional technological solutions. On the contrary, the New Space is characterized by increased commercialization, innovation, and a focus on cost reduction, accessibility, reuse, and the associated sustainability. This movement has been playing a significant role in driving innovation, reducing launch costs, and accelerating the development of large-scale satellite networks.

One of the major life-changing outcomes of the New Space is the evolution of the mega-constellations. These are large networks of interconnected satellites working together to provide various services with a focus on global communications. The mega-constellations are composed of Non-Geostationary Orbit (NGSO) satellites, in particular Low Earth orbit (LEO) satellites. European Space Agency defines LEO as an altitude of less than 1000 km but can be as low as 160 km above Earth [Eur20]. According to FCC filings, approximately 70,000 LEO satellites might populate orbit in the near future [McK]. These are ambitious projects mostly led by private companies (such as SpaceX, Amazon's Project Kuiper, and Telesat) that aim to deploy thousands of satellites for global broadband Internet coverage. It will be no surprise that there will be supplementary national or continental efforts to build new constellations. Even if all of the planned constellations do not materialize, a significant number of satellites is expected to remain in space.

On the communication technology side, these constellations are evolving to enable direct-to-device connectivity, where we will be able to connect to satellite constellations by using our regular phones. Direct connections to satellites (i.e., direct-to-cell connectivity) are already available, currently serving only low data rate applications such as emergency messaging. However, the use of different technologies is needed to increase the transmission data rates. A prominent approach that is currently being tested is the use of a very large antenna [AST]. Other solutions include the use of CubeSats in satellite swarms [TDK23] or cell-free massive multi-input muti-output (MIMO) satellite clusters [Abd+23a]. These solutions can help balance the link budget and, hence, increase the data rates. Of course, such an integrated terrestrial and satellite network promises the elimination of the digital divide and rapid disaster response.

4.2 Use-cases for Mega-Constellations

In the evolution paths, these LEO satellite networks can offer more than high-rate communication services [Abd+23b]. For instance, depending on the computational capability and the propagation conditions, each satellite can be used for computational offloading (rather than relying on a centralized cloud server). This can reduce latency and improve efficiency in applications like the Internet of Things (IoT). LEO satellites can also be used for caching by storing copies of frequently accessed data closer to the point of use. This strategy can reduce the time it takes to retrieve data, thereby reducing end-to-end communication delays.

Clearly, enhanced capabilities of these mega-constellations introduce new operational constraints as these satellite constellations are expected to work seamlessly with existing ground-based infrastructure. Interoperability is crucial for providing a smooth transition between satellite and terrestrial communication. The increasing traffic demands of the users in such a multi-purpose network with mobile network elements can be addressed by the use of different frequency bands. Terahertz (THz), sub-THz, millimeter-wave (mmWave), and Free-Space Optics (FSO) can be utilized for specific connectivity needs. Actually, this is where cognitive radio capabilities can help us coordinate and manage this highly mobile infrastructure (do not forget that an LEO satellite travels at a speed of approximately 7.8 km/sec [May22]).

4.3 Role of Cognitive Radio in Satellite Networks

The spectrum management in these mega-constellations will surely be critical, and the cognitive radio principles can help with this complicated problem. The primary goal of cognitive radio is to improve spectrum utilization, enhance communication reliability, and support the coexistence of multiple wireless communication systems in a shared spectrum. Classically, cognitive radio refers to a type of wireless communication in which a radio device can intelligently and autonomously adapt its operating parameters based on the surrounding environment and the specific needs of the communication system [MM99]. The key idea behind cognitive radio is to make more efficient use of the available radio frequency spectrum, which is a limited and valuable resource.

In the future, the dense satellite deployments can be coordinated by autonomous satellites that determine the most suitable band while sensing the environment. This can pave the way to a distributed interference management framework. The wide and multi-band cognition capability can help us determine the transmission parameters and also employ learning algorithms and decision-making processes to continuously adapt to changing environmental conditions and optimize their performance over time.

At the satellite scale, cognitive radio can bring about significant improvements by enabling autonomous decision-making and addressing various challenges in space network systems. Cognitive satellites can autonomously select transmission parameters such as frequency bands, data rates, redundancy levels, security settings, and energy levels based on real-time environmental conditions. This adaptability can help optimize communication performance and resource usage. Such a satellite furnished with cognitive capabilities can also enable cross-layer and cross-application interactions, allowing satellite clusters to consider multiple protocol layers and applications simultaneously. This holistic approach can lead to more efficient resource utilization and improved overall constellation performance. Cognitive satellites can also leverage machine learning algorithms for joint detection and estimation problems. This can enhance the device's ability to adapt to dynamic and unpredictable

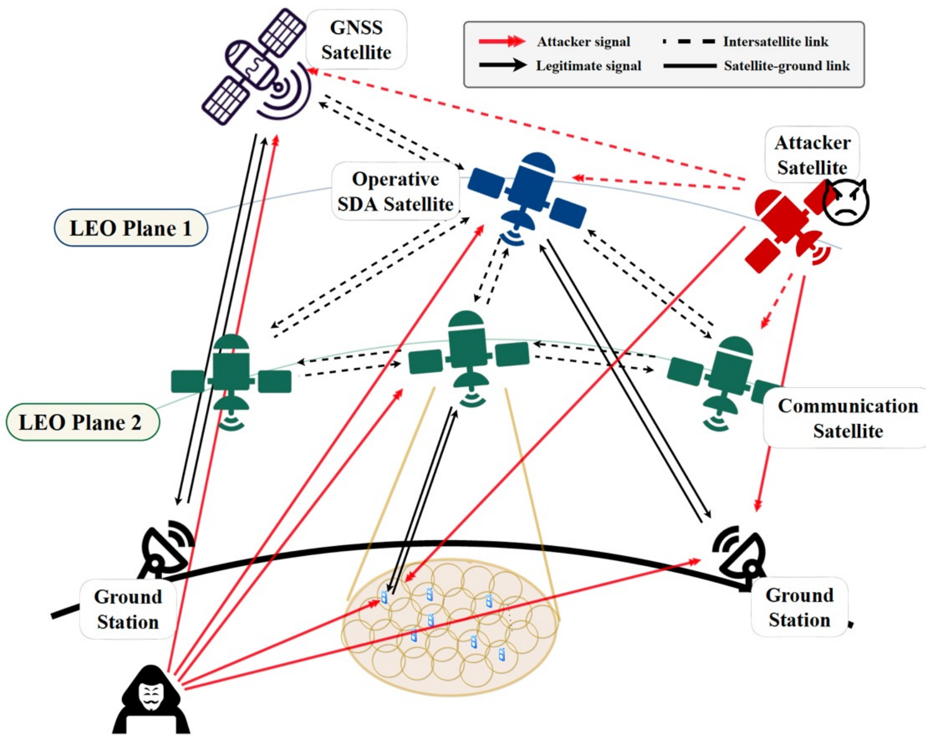


Figure 4.1: (From [COK23])The operative SDA satellite plays the role of managing and supporting all SDA applications within the constellation in LEO plane 1. The satellites in LEO plane 1 provide communications services to Earth, while a Global Navigation Satellite System (GNSS) satellite provides positioning, navigation, and timing (PNT) information to ground and space systems.

radio environments, improving signal detection and channel estimation accuracy.

The capabilities envisioned are not only limited to the physical layer. Cognitive satellites can dynamically adapt routing strategies based on current network conditions and the availability of different communication paths. This adaptability will particularly be beneficial in scenarios with changing topologies or link quality. Cognitive satellites can also support intelligent mobility management by considering factors such as spectrum availability and interference levels when deciding on handovers or reconfiguring network connections of terrestrial users.

Overall, cognitive satellites are expected to optimize the allocation of resources, including spectrum, power, and computational resources, based on the current demand and environmental conditions. This can contribute to improved efficiency and responsiveness. Cognitive satellite's ability to autonomously adapt to changing conditions can also extend to security, where satellites can dynamically adjust security levels, change encryption methods, and detect abnormal behavior, contributing to better attack detection and prevention both for the ground connections and the inter-satellite links.

4.4 Space Domain Awareness (SDA) and Evolution towards the Future

The cognitive capabilities of each satellite can also be extended to the network/constellation scale and help contribute to Space Domain Awareness (SDA) [Jah16]. SDA is expected to play a crucial role in the context of mega-constellations, Earth observation, and truly global Internet coverage. SDA involves monitoring, tracking, and understanding activities in Earth's orbit to ensure the safe and sustainable use of space. A depiction from [COK23] is shown in Figure 4.1.

SDA systems already help in continuously monitoring the positions and trajectories of satellites. This information is vital for predicting potential collisions and ensuring safe separation between satellites, minimizing the risk of accidental collisions and the creation of additional space debris.

As space becomes more and more congested, effective SDA will be essential to enhance the overall reliability and longevity of mega-constellations, contributing to the responsible use of space. Mega-constellations are expected to require frequent satellite maneuvers for operational reasons, such as maintaining proper spacing, adjusting orbits, or avoiding space debris. SDA will provide the necessary information to plan and execute these maneuvers safely, contributing to effective space traffic management by providing real-time data on the positions and movements of satellites. This information will surely be crucial for coordinating satellite operations and preventing conflicts in crowded orbital regions. Hence, SDA can contribute to tracking space debris, including defunct satellites and fragments from previous space missions. This information will be critical for avoiding potential collisions with debris and implementing mitigation measures to reduce the creation of additional space debris.

SDA systems are also expected to monitor the behavior of satellites within mega-constellations for any unexpected or abnormal activities. Detection of anomalies can trigger investigations and corrective actions to maintain the integrity and functionality of the constellation. Early detection of security issues will allow for timely responses to mitigate risks.

Note that the SDA notion is rather closely related to cognitive radio skills [Lef+22]. Mega-constellations are expected to rely on coordinated use of radio frequencies for communication. SDA already helps manage and coordinate frequency assignments, reducing the risk of interference between satellites and other space-based systems. SDA can also detect and identify anomalies in the behavior of satellites within mega-constellations. This includes monitoring for unauthorized or unexpected activities that could pose a threat to the integrity and functionality of the constellation.

The increasing congestion of Earth's orbit with satellites and space debris makes space situational awareness a critical aspect of space operations. It helps mitigate the risk of collisions, protects valuable space assets, and promotes the responsible use of space to prevent the creation of additional space debris. Organizations like the U.S. Space Surveillance Network (SSN) and international initiatives work on enhancing space situational awareness capabilities and promoting best practices for space sustainability.

4.5 Conclusion

Considering the emerging mega-constellations, the incorporation of cognitive radio technology into SDA systems can lead to more adaptive, efficient, and resilient communication networks, ultimately improving the monitoring and tracking of objects in space. The ability to dynamically adapt to changing conditions and make intelligent decisions based on real-time data will be particularly valuable in dynamic and complex space environments. Overall, the future looks bright for cognitive radio applications in the emerging space networks.

References

[Eur16] European Space Agency. *New Space and the role of public support*. *https://www.esa.int/About_Us/Business_with_ESA/Global_Space_Economic_Forum/New_Space_and_the_role_of_public_support*. 2016.

[Eur20] European Space Agency. *Low Earth Orbit*. *https://www.esa.int/ESA_Multimedia/Images/2020/03/Low_Earth_orbit*. 2020.

[McK] McKinskey & Company. *The future of space: It's getting crowded out there*. *https://www.mckinsey.com/featured-insights/the-next-normal/space*.

[AST] AST Space Mobile. *Bluewalker 3*. *https://ast-science.com/spacemobile-network/bluewalker-3/*.

[TDK23] Diego Tuzi, Thomas Delamotte, and Andreas Knopp. "Satellite Swarm-Based Antenna Arrays for 6G Direct-to-Cell Connectivity". In: *IEEE Access* 11 (2023), pages 36907–36928. DOI: *10.1109/ACCESS.2023.3257102*.

[Abd+23a] Mohammed Y. Abdelsadek et al. "Broadband Connectivity for Handheld Devices via LEO Satellites: Is Distributed Massive MIMO the Answer?" In: *IEEE Open Journal of the Communications Society* 4 (2023), pages 713–726. DOI: *10.1109/OJCOMS.2023.3253643*.

[Abd+23b] Mohammed Y. Abdelsadek et al. "Future Space Networks: Toward the Next Giant Leap for Humankind". In: *IEEE Transactions on Communications* 71.2 (2023), pages 949–1007. DOI: *10.1109/TCOMM.2022.3228611*.

[May22] Andrew May. *Low Earth orbit: Definition, theory and facts*. *https://www.space.com/low-earth-orbit*. 2022.

[MM99] J. Mitola and G.Q. Maguire. "Cognitive radio: making software radios more personal". In: *IEEE Personal Communications* 6.4 (1999), pages 13–18. DOI: *10.1109/98.788210*.

[COK23] Selen Gecgel Cetin, Berna Ozbek, and Gunes Karabulut Kurt. "Integrated Space Domain Awareness and Communication System". In: *2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring)*. 2023, pages 1–5. DOI: *10.1109/VTC2023-Spring57618.2023.10201087*.

[Jah16] Moriba Jah. "Space Surveillance, Tracking, and Information Fusion for Space Domain Awareness". In: *NATO-STOEN-SCI-292* (2016).

[Lef+22] Samuel Lefcourt et al. “Space Cognitive Communications: Characterizing Radiofrequency Interference to Improve Digital Space Domain Awareness”. In: *2022 International Conference on Localization and GNSS (ICL-GNSS)*. 2022, pages 1–7. DOI: *10.1109/ICL-GNSS54081.2022.9797033*.

The Author

Gunes Karabulut Kurt is a Canada Research Chair (Tier 1) in New Frontiers in Space Communications and AssociateProfessor at Polytechnique Montréal, Montréal, QC, Canada. She is also an adjunct research professor at Carleton University. From 2010 to 2021, she was a professor at Istanbul Technical University. She received the B.S. degree with high honors in electronics and electrical engineering from the Bogazici University, Istanbul, Turkey, in 2000 and the M.A.Sc. and the Ph.D. degrees in electrical engineering from the University of Ottawa, ON, Canada, in 2002 and 2006, respectively. From 2000 to 2005, she was a Research Assistant with the CASP Group, University of Ottawa. Between 2005 and 2006, she was with TenXc Wireless, Canada. From 2006 to 2008, she was with Edgewater Computer Systems Inc., Canada. From 2008 to 2010, she was with Turkcell Research and Development Applied Research and Technology, Istanbul. Her research interests include multi-functional space networks, space security, and wireless testbeds.

5. Interview with Prof. Ying-Chang Liang

1. Question: In your opinion, what is/are the most important topic(s) that is going to usher a new era of cognition for communication networks?

   Answer: Towards the future of cognition for communication networks, Symbiotic Communications (SC) [Lia+22] may stand out as one of important topics, which aims to greatly enhance the efficiency, adaptability, and overall performance of communication networks. By leveraging the analogy to the natural ecosystem in biology, this concept advocates the coexistence of the radio systems yet achieving mutual benefits through intelligent resource and/or service exchange, instead of harmful interferences, which may revolutionize how we think about and implement cognitive capabilities for communications and networking.

2. Question: Can you explain Symbiotic Communications to the readers?

   Answer: Symbiotic Communication (SC) rethinks the electromagnetic (EM) space as a radio ecosystem, where various radio systems, termed as symbiotic partners (SPs), form symbiotic relationships (such as mutualistic symbiosis) through intelligent resource and/or service exchanges. The radio resources include but not limited to spectrum, energy and infrastructure, while the radio services may include communicating, relaying and computing services. While each SP has its own design objective in terms of throughput, power consumption, and latency, SC considers the collective objectives of all SPs and support resource and service exchange for the purpose of achieving mutual benefits for all SPs.

3. Question: Why and how do you think this is going to impact the future wireless networks?

   Answer: In the past, the spectral efficiency can be notably improved using cognitive radio technology [MM99; Lia+11] by allowing spectrum sharing between primary and secondary users under well-designed frameworks and regulations. To make future networks more resilient and efficient, SC takes a step further by extending resource sharing beyond just spectrum to include other radio resources and services. This paradigm shift breaks down traditional boundaries between radio systems, offering a new perspective on radio resource management. By advocating the collaborations between radio systems, SC provides new guidelines for the design of future wireless communication systems. These advancements are not just about enhancing efficiency but also redefining how wireless networks operate, leading to more sustainable and adaptable communication, which is crucial for meeting the challenges of tomorrow's wireless demands.

4. Question: What are the main challenges or the remaining open problems in Symbiotic Communication? Do you have any initial insights on how to tackle those challenges?

   Answer: The main challenge for SC is how to establish proper symbiotic relationships among radio systems that make the whole radio ecosystem sustainable and adaptable. There are two potential techniques to address this challenge. One is called symbiotic coevolution, through which the SPs in SC coevolve into mutualistic symbiosis by exchanging the radio resource and service, thus the SC can be regarded as a multi-agent system. As an intelligent agent, each SP interacts with each other and makes decisions in a distributed manner, thus multi-agent reinforcement learning can be used to execute the distributed learning. The other one is called symbiotic synthesis, which artificially construct the symbiotic relationship by co-designing the SPs for collective objectives. Multiple-objective optimization can be used to model the symbiotic synthesis, in conjunction with objective function and constraint refinement introduced by resource and service exchange.

5. Question: Would you mind sharing with the readers about the research or projects that you are currently working on? Are there any interesting or intriguing results that may stimulate our thoughts?

   Answer: Currently, we are working on the general framework of Symbiotic Communications, and various specific example systems like Symbiotic Radio [Lia+20] that integrates active and passive communications. To be more specific, in SR, the active transmission achieves multipath diversity provided via backscattering in the passive transmission, while the backscatter device gains the transmission opportunity using the RF source and radio spectrum of the active transmission. Thus, this SR technique forms a mutualistic symbiosis between the active and passive communications, because of the spectrum and power sharing nature, it has the potential to support massive IoT in 5.5G and even 6G networks.

6. Question: How do you think academia, industry and government can engage to solve not only the fundamental problems, but create an ecosystem to be adopted for practical usage?

   Answer: The engagement of academia, industry, and government is indeed vital for the development of new techniques in wireless communications. There are quite a lot of academic studies on SR now, and interestingly, those studies have attracted attention from industry for the development of ambient and passive IoT. The engagement of government agencies is important for spectrum regulations and to create an ecosystem for practical usage.

7. Question: How do you think academia, industry and government can engage to solve not only the fundamental problems, but create an ecosystem to be adopted for practical usage?

   Answer: The engagement of academia, industry, and government is indeed vital for the development of new techniques in wireless communications. There are quite a lot of academic studies on SR now, and interestingly, those studies have attracted attention from industry for the development of ambient and passive IoT. The engagement of government agencies is important for spectrum regulations and to create an ecosystem for practical usage.

References

[Lia+22] Ying-Chang Liang et al. "Symbiotic Communications: Where Marconi Meets Darwin". In: *IEEE Wireless Communications* 29.1 (2022), pages 144–150. DOI: *10.1109/MWC.101.2100132*.

[MM99] J. Mitola and G.Q. Maguire. "Cognitive radio: making software radios more personal". In: *IEEE Personal Communications* 6.4 (1999), pages 13–18. DOI: *10.1109/98.788210*.

[Lia+11] Ying-Chang Liang et al. "Cognitive radio networking and communications: an overview". In: *IEEE Transactions on Vehicular Technology* 60.7 (2011), pages 3386–3407. DOI: *10.1109/TVT.2011.2158673*.

[Lia+20] Ying-Chang Liang et al. "Symbiotic Radio: Cognitive Backscattering Communications for Future Wireless Networks". In: *IEEE Transactions on Cognitive Communications and Networking* 6.4 (2020), pages 1242–1255. DOI: *10.1109/TCCN.2020.3023139*.

Prof. Ying-Chang Liang

Ying-Chang Liang (F'11) is a Professor with University of Electronic Science and Technology of China, China. He was a Professor in the University of Sydney, Australia, and a Principal Scientist in the Institute for Infocomm Research (I2R), Singapore, and a Visiting Scholar in Stanford University, USA. His research interests include 5G/6G networks, cognitive radio, dynamic spectrum access, symbiotic radio, green communications and passive Internet-of-Things.

Dr. Liang is a Fellow of IEEE, and a foreign member of Academia Europaea. He has been recognized by Clarivate Analytics as a Highly Cited Researcher for ten consecutive years since 2014. He is the recipient of numerous paper awards, including the IEEE Communications Society Best Survey Paper Award in 2023, the IEEE Communications Society Award for Advances in Communications in 2022, the IEEE Communications Society Stephen O. Rice Prize in 2021. He also received the Recognition Award and Publication Award from the IEEE Communications Society Technical Committee on Cognitive Networks in 2018 and 2020, respectively.

Prof Liang was the Founding Editor-in-Chief of the IEEE Journal on Selected Areas in Communications—Cognitive Radio Series from 2011 to 2014. Through his leadership, the Series was spined off as a standalone journal, IEEE Transactions on Cognitive Communications and Networking, for which he served as the Editor-in-Chief from 2019 to 2022. He served as the Chair of the IEEE Communications Society Technical Committee on Cognitive Networks, the TPC Chair and the Executive Co-Chair of IEEE Globecom'17, which was held in Singapore.

6. Interview with Prof. Sofie Pollin

1. Question: In your opinion, what is/are the most important topic(s) that is going to usher a new era of cognition for communication networks?

   Answer: In my view, cognition means understanding what you see or measure. Instead of just inverting the channel without understanding it. Future wireless networks will understand what is happening around us, and use this cognitively.

   On another dimension, I also believe future networks will be more data-driven than model-driven. Like what is happening in the computer vision domain, we will see/understand our environment using deep learning.

2. Question: Can you explain the topics in details for the reviewers?

   Answer: I mean that from the channel, we will measure Doppler and speed of obstacles in our environment. We will understand if a blocker impacting our mmWave link is approaching. We know how fast we move and if we should handover to a larger cell. We also understand if we moved from outdoor to indoor and can handover to an indoor cell.

   As this understanding will be data-driven, or learned from data, there will be a huge need for labeling wireless signal channel or propagation data. As we have already a lot of sensors around, such as camera's, IoT sensors, Lidar, it is in principle feasible to use such information to label our wireless data. It is just needed to store all that data, and position all measurements well in time and space.

3. Question: Why and how do you think this is going to impact the future wireless networks?

   Answer: Beyond ubiquitous coverage for communication, we will now also have ubiquitous coverage for sensing. As radios and networks will understand their environment, they will be able to reason about it and evolve in a way beyond their initial design. This is scary at first, as how can we guarantee interoperability and standard compliance of such evolving radios and networks? But they will evolve of course within a set of fixed interfaces, to ensure interoperability. The opportunity however lies in the fact that radios will evolve over time, and hence will have a much longer lifetime. But this evolution is more than a generic software upgrade. This evolution ensures our radios and networks learn over time to communicate and sense with the best efficiency. Life-long learning for radios somehow ;-)

4. Question: What are the main challenges or the remaining open problems in the data-driven approach? Do you have any initial insights on how to tackle those challenges?

   Answer: The main challenges are in my view labeled data and regulation. We need good quality labeled data to train our radios and cognitive networks. But we also need some guidelines that bound the flexibility we offer to these cognitive networks.

5. Question: Would you mind sharing with the readers about the research or projects that you are currently working on? Are there any interesting or intriguing results that may stimulate our thoughts?

   Answer: We are currently working a lot on integrated communication and sensing. Our focus is primarily on integrated communication and localization, as a lot of use cases also benefit from the localization of transmitters. We also focus on passive sensing. For me, the most interesting use cases of passive sensing involve human sensing, such as human activities or vital signs. Our cognitive network can then adapt to the environment and the human it is serving. Some of the most interesting outcomes are that you don't really need high frequencies or super high bandwidths for a lot of relevant applications, and a lot of sensing could be achieved already with current 4G and 5G systems.

   Or course, one of our favorite topics is also aerial communication, which is taking up quickly. Not only for unmanned aerial vehicles, but also non-terrestrial networks in general are considered. I particularly believe in aerial nodes as they have a super good view of all that happens in our environment. They are also very agile and can move there where they are needed. So, we could have a super high density everywhere there is something interesting happening, relying on mobile nodes that can move there where needed. This is interesting as it might make future networks so much more sustainable and deployable. Imagine some very high helicopter cells that just manage our cognitive networks from the sky. Imaging radios that are there where they are needed, and fly to the next location when there is no need any more for extra capacity in the current location.

6. Question: How do you think academia, industry and government can engage to solve not only the fundamental problems, but create an ecosystem to be adopted for practical usage?

   Answer: I think they should engage in training our future engineers. Young creative minds should find ways to work together with experienced industry experts. I also believe that technology evolutions should be supported by society. Technology should be sustainable, fair, available to all generations and communities.

7. Question: How do you think we, as a community, can engage with next generation of communications engineers to contribute towards solving the problems stated above?

   Answer: As a community, I think we should invest in the sharing of knowledge. Knowledge can be represented in publications, from mathematical models and optimizations. More and more knowledge is however included in datasets, labeled datasets and simulations or learned models. We have to invest in sharing of models, and reuse of datasets and benchmarks. Availability of good labeled benchmarks is probably the first and most important requirement for enabling future research progress.

Prof. Sofie Pollin

Sofie Pollin is a professor at KU Leuven focusing on wireless communication systems. Before that, she worked at imec and UC Berkeley, and she is currently still a principal member of technical staff at imec. She received the Ph.D. degrees from KU Leuven, Belgium, in 2006. Prior to that, she was with the University of California, Berkeley, as a Postdoctoral researcher working on cognitive radio. Her research centers around wireless networks that require networks that are ever more dense, heterogeneous, battery powered, and spectrum constrained. Her research interests are cell-free networks, integrated communication and sensing, and non-terrestrial networks. She built a 5G testbed for distributed Massive MIMO at KU Leuven, is involved in a spectrum sensing open data initiative, and is now leading the way towards 6G tests in multiple large EU projects.

7. Interview with Prof. Krishnamachari

1. Question: In your opinion, what is/are the most important topic(s) that is going to usher a new era of cognition for communication networks?

   Answer: In my view, the future of cognition in communication networks will be significantly shaped by three emerging topics: a) the integration of Generative AI models like LLMs in network design, operation, and interaction; b) the application of Graph neural networks in crafting advanced communication network algorithms; c) the deployment of multi-agent reinforcement learning for managing networks as interconnected systems of intelligent agents.

2. Question: Can you explain the three topics to the readers?

   Answer: The integration of Generative AI models, particularly Large Language Models (LLMs) like GPT-4, in network design, operation, and interaction represents a significant step forward in the evolution of cognitive networks. These advanced AI models bring a transformative approach to how networks are conceptualized, implemented, and managed.

   Firstly, in network design, LLMs could potentially help engineers in designing more efficient and effective network architectures, tailored to specific needs and capable of adapting to changing conditions.

   In terms of operation, LLMs can automate and optimize many routine tasks, from traffic management to predictive maintenance. They can process and interpret large streams of network data as well as sensor data communicated over IoT networks in real-time.

Lastly, LLMs significantly improve the interaction between human operators and network systems. They enable more natural and intuitive interfaces, allowing operators to query and control networks using conversational language. This reduces the complexity of network management, making it more accessible to a broader range of users, reducing the likelihood of human-error and helping users manage ever-more complex networks.

3. Question: Why and how do you think this is going to impact the future wireless networks?

   Answer: As our networks become larger and more complex, the need for sophisticated design and management tools grows. The utilization of LLMs offers a promising solution, aiding in both network design and management, making our future wireless networks more efficient and intelligent. When we couple LLMs with other ML tools like graph convolutional networks and multi-agent reinforcement learning, we are making a big step towards making these networks truly autonomous in their operation.

   Years ago, I had this vision of large-scale wireless networks running themselves, the reason I named my research group at USC the Auonomous Networks Research Group (*https://anrg.usc.edu*). With the ongoing advances in AI and ML, I think we are much closer to that vision becoming a reality than ever before.

4. Question: What are the main challenges or the remaining open problems in the three topics that you discussed? Do you have any initial insights on how to tackle those challenges?

   Answer: At this stage the field is truly wide open, we have not even scratched the surface of what is possible. There are a lot of low hanging fruit in demonstrating different ways in which LLM's as well as other generative AI tools and multi-agent reinforcement learning-based agents can be used to operate and manage today's networks as well as aid in designing and evaluating tomorrow's networks.

5. Question: Would you mind sharing with the readers about the research or projects that you are currently working on? Are there any interesting or intriguing results that may stimulate our thoughts?

   Answer: In one strand of ongoing work, we have been looking at different ways in which LLMs can be applied to networking. For example they can help with cybersecurity in networks by providing explainability to ML model outputs in the context of DDoS detection, helping human administrators understand what exactly is going wrong when an anomaly is detected. We are also exploring how an LLM can provide an easy interface for humans to query the data coming from an IoT deployment to understand the significance of different patterns in the IoT data - it's like having a high quality human-interpretable data analysis engine for the IoT baked into the system. We are also exploring how LLM's ability to generate software can be used to facilitate no-code re-programming of IoT systems - can a human administrator simply tell an LLM how they want a given network/distributed system to be configured and have the LLM actually generate the requisite code to make that happen?

In another strand of research, we have been using graph convolutional networks to speed up the process of scheduling complex computations on networks of edge and cloud devices. We find that we get performance comparable to state of the schedulers while generating schedules 3-4 orders of magnitude faster. This allows compute schedules to be generated rapidly for dynamic and mobile edge network settings where the topology or network conditions might be changing on a fast time-scale.

Finally, we have also been exploring how multi-agent RL can utilized with and be used to operate and optimize wireless networked systems.

6. Question: How do you think academia, industry and government can engage to solve not only the fundamental problems, but create an ecosystem to be adopted for practical usage?

   Answer: Academics today perhaps need more support than ever before from industry and government to procure computational and data resources for their research, and to train the next generation of data-driven cognitive networking experts. Academics should also be mindful that they could benefit from closer interactions with industry researchers to identify what problems are worth solving, and to collaborate on those meaningful problems with access to real-world datasets. Academics also need to collaborate with each other and industry practitioners better to support, benchmark, and wherever meaningful also use available algorithms, datasets, open-source frameworks, so that we are not duplicating effort and can give each support in contributing to the wider community. To build a thriving ecosystem requires us all to see the benefit of working collaboratively.

7. Question: How do you think we, as a community, can engage with next generation of communications engineers to contribute towards solving the problems stated above?

   Answer: Engaging with the next generation of communications engineers is crucial for addressing the emerging challenges in our field. In this era of rapid technological advancement, it's essential to prioritize learning and knowledge-sharing. This can be achieved through various educational and interactive platforms.

Firstly, developing a robust curriculum that includes tutorials, summer schools, and online courses is key. These resources should not only cover fundamental concepts but also the latest advancements in communication technologies. By providing in-depth and up-to-date educational content, we can ensure that aspiring engineers are well-equipped with both the theoretical knowledge and practical skills needed in this fast-evolving landscape.

Moreover, creating more interactive platforms for dialogue and collaboration between academia and industry is vital. Workshops, conferences, and symposiums where seasoned professionals and academics can share their insights and experiences with budding engineers will foster a more cohesive learning environment. These events can serve as breeding grounds for innovative ideas, offering the next generation real-world perspectives and networking opportunities.

We also need to leverage the power of online learning platforms and social media to create virtual communities. These communities can facilitate ongoing discussions, mentorship programs, and collaborative projects, bridging the gap between theoretical learning and practical application. They can also serve as a support system for young engineers, providing guidance and encouragement as they navigate the complexities of the field.

Additionally, implementing industry internships and collaborative research projects can provide hands-on experience. By working on real-world problems, young engineers can gain valuable insights into the practical aspects of network design and operation, preparing them for future challenges in their careers.

Prof. Bhaskar Krishnamachari

Bhaskar Krishnamachari is a MIng Hsieh Faculty Fellow and Professor of ECE and CS at the Viterbi School of Engineering, University of Southern California. He directs the Autonomous Networks Research Group (https://anrg.usc.edu) . He works on emerging technologies like AI, Blockchain, and Connected IoT systems and their applications, with an emphasis on networked and distributed systems. He has co-authored three books and more than 300 papers, collectively cited more than 30,000 times. Honored as an IEEE Fellow in 2023 for his contributions to wireless networks, he is the recipient of an NSF CAREER Award, and was featured in Popular Science's "Brilliant Ten" (2015) and MIT TR-35 (2011). He has received many best paper awards including at ACM Mobicom and IEEE/ACM IPSN. He received his B.E. in Electrical Engineering at The Cooper Union (1998), and his M.S. (1999) and Ph.D. (2002) also in Electrical Engineering from Cornell University.

8. Interview with Dr. Nada Golmie

1. Question: In your opinion, what is/are the most important topic(s) that is going to usher a new era of cognition for communication networks?

   Answer: The future of communication networks is being shaped by two transformative aspects. Firstly, the evolution of communication systems is now focusing on integrated data processing moving beyond traditional data transportation to data processing during collection. Secondly, a shift from connecting people to predominantly interlinking devices, is projected to increase from 29 billion in 2022 to over 125 billion IoT devices by 2030. This shift, contributing to over 90% of total communication traffic by 2030, emphasizes the importance of sensor fusion for enhanced system optimization, marking a significant leap in imbuing communication networks with cognitive capabilities.

2. Question: Can you explain the two topics that you mentioned above for our readers?

   Answer: In the rapidly expanding IoT landscape, the copious data generated is crucial for AI/ML model training, offering extensive environmental insights and control capabilities. However, the burgeoning sensor data threatens to overwhelm existing communication capacities, necessitating a paradigm shift towards edge-based AI/ML training. This shift towards local and distributed processing, driven by advancements in semiconductor and hardware technologies, addresses challenges in latency, energy efficiency, robustness, and autonomy.

3. Question: Why and how do you think this is going to impact the future wireless networks?

   Answer: The profound impact of AI/ML on wireless network is evident, particularly in critical areas such channel modeling, spectrum sharing, beamforming, scheduling, configuration and optimization. In situations where the characterization and modeling of intricate physical phenomena present challenges, AI and ML have emerged as transformative tools.

   This transformative trend is expected to advance further with the ongoing development of telecom specific large language models. These models are poised to expedite hardware design, FPGA programming, complex wireless protocol understanding and development, enhance efficiency in training and troubleshooting processes. Analogous to the transformative influence witnessed in natural language understanding and processing through ChatGPT, the integration of AI/ML in telecommunications signifies a pivotal shift in optimizing network functionalities.

4. Question: What are the main challenges or the remaining open problems in these topics? Do you have any initial insights on how to tackle those challenges?

   Answer: Several challenges persist in integrating AI/ML with wireless communications. Key among them is managing the limited bandwidth of wireless networks and the need for local data processing. Edge computing, while promising, faces constraints in computational resources, necessitating research into lightweight, distributed AI/ML implementations. Balancing complexity and simplicity in solutions, particularly for applications like autonomous driving, remains a critical concern.

   Moreover, the environmental impact of hyperconnectivity and data overconsumption cannot be overlooked, necessitating energy-efficient solutions in the transition from 4G to 5G networks and beyond. While we are witnessing improved energy efficiency – the chip-level energy per one bit transition in processors is decreasing to about 10 attojoules (10-17 J), the power consumption in the evolution from 4G to 5G is about 4 times more as we need around 2 to 3 times smaller cells to obtain full coverage at higher frequencies. Addressing these challenges could involve optimizing algorithms for reduced computational complexity.

   Additional open problems and research gaps have been identified by the recently published NIST SP 1293.

5. Question: Would you mind sharing with the readers about the research or projects that you are currently working on? Are there any interesting or intriguing results that may stimulate our thoughts?

Answer: Our current research focuses on developing high-precision, context-aware millimeter-wave RF channel sounders, complemented by panoramic cameras and LiDAR systems. We have been using our LIDAR and camera systems, applying AI and ML to accelerate the processing of the RF measurement.

We have been looking at various sensing applications, including human sensing and gesture recognition. We have been working with the community, through the NextG Channel Model Alliance to support the dissemination of AI-ready RF propagation measurement data and models.

We have also been investigating joint communication and sensing, explored PHY layer and system-level techniques and related performance trends.

6. Question: How do you think academia, industry and government can engage to solve not only the fundamental problems, but create an ecosystem to be adopted for practical usage?

   Answer: NIST fosters collaborations through various programs, including the grant-based Professional Research Experience Program, in addition to offering Internships and Post Doc opportunities to students to further their education and gain valuable laboratory experience working at NIST.

   An example of ecosystem creation is the NextG Channel Model Alliance, comprising over 180 organizations focused on channel propagation data best practices. Such collaborative efforts are crucial for addressing complex challenges in wireless communications.

7. Question: How do you think we, as a community, can engage with next generation of communications engineers to contribute towards solving the problems stated above?

   Answer: Addressing the multifaceted challenges in wireless communications increasingly demands collaborative efforts. Recent trends show a rise in government and industry-funded research centers and initiatives, such as the PAWR platforms and the NSF-led RINGS program, involving multiple industry leaders. These multidisciplinary and collaborative projects, I believe, are key to accelerating the development of next-generation wireless communications.

Dr. Nada Golmie

Nada Golmie received her Ph.D. in computer science from the University of Maryland at College Park. Since 1993, she has been a research engineer at the National Institute of Standards and Technology (NIST). From 2014 until 2022, she served as the chief for Wireless Networks Division at NIST. She is an IEEE Fellow, and a NIST Fellow in the Communications Technology Laboratory. Her research in media access control and protocols for wireless networks led to over 200 technical papers presented at professional conferences, journals, and contributed to international standard organizations and industry led consortia. She is the author of "Coexistence in Wireless Networks: Challenges and System-level Solutions in the Unlicensed Bands," published by Cambridge University Press (2006). She leads several projects related to the modeling and evaluation of future generation wireless systems and protocols and serves as the NextG Channel Model Alliance chair.

9. Interview with Prof. Josep Jornet

1. Question: It was in 2018, i.e., five years ago, when the 3GPP first released 5G. Considering the 10-year gap between wireless generations, we are halfway through the cycle. What shall we expect to see in 6G?

   Answer: That's both true and scary. Indeed, we expect the first flavor of 6G to be released in 2028-2030, and many technologies are supposed to make it into the standard. Some of these technologies look at expanding the existing ground infrastructure with reconfigurable intelligent surfaces that can engineer the propagation of signals along the channel or at taking such infrastructure above the ground with non-terrestrial networks that include unmanned aerial vehicles, high-altitude platforms, and Earth-orbiting satellites. All this massive infrastructure will not only be used for communications but also for sensing in different flavors, from vehicular radar to climate monitoring, and all orchestrated with artificial intelligence. Of course, realizing this vision while supporting the always-increasing number of wirelessly connected devices and their thirst for higher data rates will require the adoption of new spectral bands.

2. Question: What frequency bands will enter the game in 6G?

   Answer: There are two clear trends: the mid-bands (i.e., the frequencies between 7 and 20 GHz) and the sub-terahertz band (i.e., the frequencies between 100 and 300 GHz). The former can provide a linear increase in bandwidth to existing applications while not yet suffering from the more challenging propagation that the millimeter-wave spectrum (>30 GHz) suffers. The latter will provide the drastic increase in bandwidth needed, for example, to wirelessly deliver ultrabroadband connectivity to areas where optical fibers cannot be deployed or to provide seamless access to virtual and extended reality worlds to everyone, everywhere. Of course, this comes with the cost of more challenging propagation.

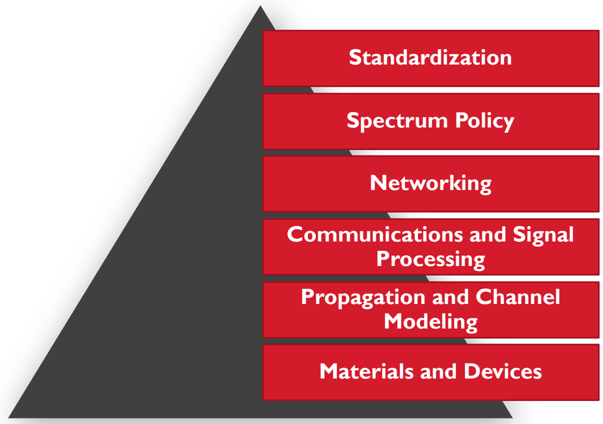
3. Question: Why stop at 300 GHz?

   Answer: As much as I would like to say that we are going to see true terahertz communications in 6G, i.e., systems that operate all the way up to a few THz, I am afraid that this is not going to be the case, due to multiple reasons that span across all aspects in the development of a new wireless technology, from technology readiness level to actual spectrum policy and standardization.

4. Question: Can you elaborate on those? What are the main challenges in sub-terahertz and terahertz communications?

   Answer: Let's use the pyramid below to describe the state of the art in terahertz communications and sensing, what has already been addressed, and what still needs to be solved in a bottom-up approach:

   - Materials and Devices: For many years, all papers on terahertz communications started by stating that there was a "technology gap" that made terahertz research mostly theoretical and, to some extent, highly hypothetical. Today, that gap is almost closed. Let me elaborate. First, the three main building blocks of a terahertz radio include the analog front end, the antenna system, and the digital back end. In terms of analog front ends, thanks to major progress in electronic, photonic, and plasmonic technologies, radios operating up to a few THz with bandwidths ranging from tens to a few hundred GHz have been demonstrated. For example, you can buy terahertz frequency-multiplying up- and down-converters based on Schottky diode technology from several vendors in the USA, such as Virginia Diodes Inc. Similarly, fixed directional antennas and lensing systems that work across the whole terahertz band are commercially available. When it comes to the digital back end, while you could use any existing software-defined radio (SDR) platform, the challenge is to process tens



to hundreds of GHz of bandwidth in real-time. You might want to check out the new USPA platform for Keysight, or you can ask me for our latest Radio-Frequency on System-on-Chip (RFSoC)-based engine able to process close to 10 GHz of bandwidth in real-time. Now, the question is: do we have a terahertz radio that could be incorporated into cell phones today? The answer is no, but much work is happening in that direction, particularly regarding integration and thermal packaging, and I'm confident that such a system, at least in the 100-300 GHz range, will soon be out.

- Propagation and Channel Modeling: Another common myth was that the terahertz channel was "too bad to be used" in practical applications, especially because of the absorption by water vapor molecules. And, indeed, the absorption by water vapor molecules can easily exceed hundreds of dBs over tens of meters, but only at some very specific frequencies, known as absorption lines. In between those lines, there is plenty of available bandwidth. We refer to those bands as the "absorption-defined" transmission windows and each can individually exceed 100 GHz of bandwidth. Therefore, if you want to avoid absorption, you can. Of course, there might be applications in which absorption and the unique distance-dependent bandwidth that it introduces can come to your advantage (think of physical layer security). Now, besides molecular absorption, there is another usually misinterpreted factor: the spreading losses or free-space path losses. The spreading losses compute the power that an omnidirectional antenna would intercept at a distance from another omnidirectional radiator. Because at terahertz frequencies, the wavelength is very small (from a few millimeters down to tens of micrometers), a terahertz omnidirectional antenna (e.g., a half-wavelength), is very small and, thus, has a very small physical area, meaning, it can only intercept a very small fraction of the power density at a distance of the source. Of course, the solution is to make antennas larger, more than just half a wavelength, but then such antennas intrinsically become directional. This is why people often state that "terahertz antennas are directional," but they are not: we choose to design them to be directional because we need them to be large. The exciting news is that, for a fixed antenna footprint (e.g., think of the space current antennas occupy on your cellphone), we can squeeze many more THz wavelengths than, for example, 2.4 GHz wavelengths, which means that in the same footprint, we can have many directional gains. Not only that, if both transmitter and receiver are directional, but the propagation losses at THz frequencies can also be lower than those at lower frequencies... if we can 1) align them and 2) ensure the radiation is not blocked. And those are the challenges, particularly blockage. In parallel with all these "clarifications," in the last five years and with the closing of the THz technology gap, many groups have focused on experimentally characterizing the THz channel through massive channel-sounding campaigns in many different scenarios. While we are not a channel-sounding group, we tried to answer a question that we often get asked: Will terahertz communications work in rain or snow? The answer: yes, they will and, again, better than what people think (and certainly much better than optical systems).

- Communications and Signal Processing: Once we know what THz technology can do and what the channel will do to THz radiation, we can start designing the signals that can make the most out of the two. Let me start with a disclaimer: If you ask me what the waveform is for THz 6G systems, I am afraid I don't have an answer. Will we use OFDM, like in 5G? We could, and several groups, including yours, have shown that it is possible. However, the Peak-to-Average Ratio (PAPR) is real, and we don't have much power to space in safety margins "in case of that peak." Could we adopt lower PAPR variations of OFDM, such as DFT-Spread-OFDM? We could, and, in fact, in many of our recent experimental works, we have based our physical layer on this modulation technique. How about OTFS? Yes, this modulation is robust against frequency fluctuations, such as Doppler shifts in mobile systems or, more relevant to THz systems, high phase noise. If you think of all these techniques, they are aimed at "fighting" the THz channel, and that's the usual driver. However, in our group, we have also been exploring modulations that are only possible because of the behavior of the THz channel. For example, over very short distances (literally under one meter) or in scenarios with extremely low humidity (i.e., no water vapor molecules to absorb our signal), sub-picosecond-long pulses with a few THz of bandwidth can be utilized for simple, very high-speed non-coherent communications. As we increase the communication distance and/or the number of absorbing molecules, the absorption lines broaden, or the absorption-defined transmission windows shrink. This phenomenon leads to a very unique distance-dependent bandwidth of THz systems. In our group, we have proposed new modulations that allow the simultaneous transmission of different streams to users in the same direction by combining concatenated modulators operating at different symbol rates. Of course, many other ways exist to leverage the very large bandwidths. For example, if one is willing to trade spectral efficiency by robustness, spread spectrum techniques can be adopted. Those will come in handy later on when we talk about spectrum sharing.
- Networking: This is where most work is needed. Working on the networking

aspects didn't make much sense before we understood all the previous points. In our group, in light of the very high directivity that will be needed simultaneously at the transmitter and the receiver to close an ultrabroadband link over meaningful distances, we have proposed new receiver-initiated medium access control protocols that shift from the typical "transmitter-pushed-based" approach to a "receiver-pulling-based" approach. At the same time, using higher gain antennas is not the only way to increase the communication distance; for example, relaying and multi-hop communication make more sense than ever. Compared to lower frequency systems, including millimeter-wave systems, reducing the transmission distance leads not only to higher signal-to-noise ratios (and, thus, higher modulation orders) or transmission power savings but also to larger transmission bandwidths (again, because of the behavior of molecular absorption). Moreover, reducing the transmission distance and, thus, relaxing the antenna directivity requirements leads to faster neighbor/beam discovery and tracking procedures, reducing the latency on a per-hop basis and, ultimately, increasing the end-to-end throughput, which at the end of the day is the only performance metric a user cares about: what's the point of having a physical layer able to support terabits per second, if we can only get to use it after an hour of setup time? (I'm exaggerating, but you get my point...). For the time being, all these studies have relied mostly on numerical models and simulations, including those with TeraSim, our open-source ns-3 extension to simulate terahertz networks that incorporates all the models for the THz hardware and THz channel described above, as well as two different physical layers, first released back in 2018. The challenge is to experimentally test this because, as opposed to channel sounding or physical layer experiments, we do need a real-time ultra-broadband digital back-end, and literally, we are just building those.

- Spectrum Policy and Standardization: For many years, we used to talk about the terahertz band as "no man's land," but the reality is very different: within the THz band, several frequencies are critical to the scientific community. They claimed those in the ITU World Radiocommunication Conference back in 2001 and, as a result, today, the sub-THz band is chopped in by multiple forbidden frequencies, in which no emission is allowed. As a result, today, the largest contiguous band that can be legally utilized for communications between 100 and 200 GHz is 12.5 GHz. The situation is not much better between 200 and 300 GHz. Of course, we can continue to go up, but as you can imagine, the technology does not get any better (but is much more challenging). Interestingly, these protected frequency bands are primarily utilized by some radio telescopes and Earth Exploration Satellite Services. Because of the limited transmission power of THz radios and the aforementioned propagation peculiarities of THz radiation, full prohibition of the bands seems to be overkill: unless you are in the vicinity of a radio telescope, the chance for you to interfere with a THz sensor is limited to the temporal window over which a THz-capable satellite might orbit over you (i.e., a few minutes per day at most). That's why we are working on more efficient ways to share the spectrum between communication and sensing users, which can benefit both communities and allow everyone to use more bandwidth dynamically. Finally, in relation to standardization, it is relevant to know that the first standard for THz communications was approved in 2017 and has just been revised in 2023. This is the IEEE 802.15.3d and mostly defines point-to-point links. While far from a cellular or mobile wireless standard, it does cover multiple relevant scenarios, such as wireless backhaul applications.

5. Question: Can you share the research or projects you are currently working on with the readers? Are there any interesting or intriguing results that may stimulate our thoughts?

   Answer: In addition to working on many of the challenges I have just mentioned, two projects are particularly exciting these days: near-field terahertz communications and terahertz satellite communications.

   Let's start with the first. I have repeatedly mentioned that the solution to the high spreading losses is to use directional antennas, which are much larger than just "half a wavelength." As a result, their Fraunhofer distance, or one of the boundaries we use to define a radiator's far-field propagation regime, is very large. For example, for a 10 cm wide antenna at 120 GHz, the far field does not start until 8 m. The same antenna at 300 GHz will operate in the far field only after 20 m. If, instead of a compact antenna, we think of a larger one on a base station, things get even more interesting. For example, a 1 m antenna has a far field of 800 m at 120 GHz or 2 km at 300 GHz. This means that most THz mobile systems will be operating in the near field. And why do we care about this? Mostly because all the beam management strategies (e.g., beam forming and beam steering algorithms) developed to date are designed for far-field operation and simply do not work well in the near-field.

   To overcome this challenge, several groups have started to work on defining beam management strategies that mimic the behavior of a focusing lens. The problem with beam-focusing is that, compared with far-field beam-forming strategies, in which we mostly need to pick "a direction" for our beam, now we need to take into account the "depth" of the user: stepping back and forth, even within the same beam, results in the user being "out of focus," and, thus, new channel state information is needed to refocus. This leads to significant signaling overhead and, once again, impacts what the user will perceive: latency and throughput, as opposed to "ideal physical layer bit-rate."

   Instead, my group thinks of being in the near field as an opportunity, more than a challenge. Particularly, if we are in the near field, besides launching "Gaussian-shaped" beams (as in the far field) or "focused beams" as with lenses, we can send, for example, beams whose intensity and phase profiles resemble that of a Bessel function. Interestingly, Bessel beams focus along a line in the near field, i.e., you can achieve in the near field what traditional beam forming achieves in the far field and, thus, only "the direction" to focus on is needed, as opposed to a focal point. Moreover, Bessel functions are self-healing: unless they are fully blocked, Bessel beams will regenerate after an obstacle. Therefore, being in the near field and adopting Bessel beams can ultimately overcome what we already described as the main problem of the THz channel, i.e., blockage. Moreover, Bessel beams are just one of the main types of beams that can be defined. Others include bending Airy beams, which can be programmed to turn in different directions at a given density, effectively going around corners, for example. On top of these different types of beams, we can further incorporate orbital angular momentum or OAM, which means that we can twist the beams in space as they propagate to generate spatially orthogonal channels and, thus, increase the MIMO capacity of the system. Of course, there are many challenges associated with all these, including how to dynamically generate different types of beams (hint: we can use reconfigurable intelligent surfaces to do so), understanding how the channel models in the near field differ from those in the far field, how interference between different types of beams is resolved, or how we coordinate mobile users that transition from the near field to the far field and vice versa.

Focusing next on the second topic (no pun intended…), let's talk about terahertz communications in space. Traditionally, because of everything we have mentioned, people thought terahertz communications were good only for short distances. However, this is not the case. For example, in collaboration with the NASA Jet Propulsion Laboratory and the US Air Force Research Laboratory, we have demonstrated a multi-gigabit-per-second 2-km-long link at 225 GHz, utilizing 40 dBi antennas. With the same technology, utilizing advanced atmospheric propagation models, we have numerically shown that satellite access links (ground to satellite and satellite to ground) at terahertz frequencies are possible. Moreover, when it comes to inter-satellite communications, the terahertz band can support bit rates comparable to that of optical systems and do so with relaxed pointing requirements. Moreover, by carefully selecting the frequency band of operation, inter-satellite links can be designed to be "protected" from jamming and eavesdropping from the ground by the atmosphere itself. For now, these results are all theoretical or numerical (for example, relying on our simulation platform that integrates an orbital simulator with a communication link emulator). However, we are trying to change this: with the support of the NASA CubeSat Launch Initiative, we have been approved to launch two small satellites that will be utilized first to test inter-satellite links and then access links. More details will be following soon, but we are talking about a launch by 2027.

6. Question: How do you think academia, industry, and government can engage to solve not only the fundamental problems but also create an ecosystem to be adopted for practical usage?

   Answer: Let me be controversial here. Many of the recent efforts by funding agencies have been focused on precisely having industry and academia work together in order to solve immediate problems, which is fantastic. At the same time, finding funding opportunities that can support fundamental, very high-risk, potentially transformative research is becoming harder and harder. The only way in which, as a nation, we can be at the forefront of science and technology is by supporting research for which we don't have a clear answer and acknowledging that failure is part of the research process. If we just do "what everyone is doing because that's what we know will work," it will be much harder to lead new fields and research directions that can potentially transform society.

What's the solution to this? We should sustain and even increase the programs with industry, but at the same time, we should match, if not increase, the support for fundamental research. This funding should not only be for core "sciences" but also for "engineering," where I include communications and networking. Moreover, as reviewers (in panels, in papers, etc.), we should be willing to endorse proposals for which the researchers don't have all the answers: isn't that the whole point of research?

7. How can we, as a community, engage with the next generation of communications engineers to contribute towards solving the problems stated above?

   Answer: Indeed, this is one of the biggest challenges our community is facing. Today, water, electricity, and Internet access are utilities, and this is, in fact, great. However, as a result, the younger generations do not perceive them as exciting: is there anything exciting in designing new water pipes? We have water, "water pipes" work... so the same with "data pipes," isn't it? The problem is that while we are not trying to consume more water (the contrary, in fact...), we have new applications that require more data, such as extended reality, and existing data pipes cannot support the data rates needed for immersive group activities. Moreover, perhaps even more importantly, current "data pipes" are not the same size for everyone, and, in fact, there are areas where those pipes are non-existent or very narrow.

   Addressing this societal need is how the excitement should start. Then, incorporating new tools (e.g., Artificial Intelligence), aiming for new application scenarios (e.g., Non-Terrestrial Networks) and even adopting new physics (e.g., Quantum Information Processing) will only help.

Prof. Josep Jornet

Josep Miquel Jornet is a Professor in the Department of Electrical and Computer Engineering, the director of the Ultrabroadband Nanonetworking (UN) Laboratory, and the Associate Director of the Institute for the Wireless Internet of Things at Northeastern University (NU). He received a Degree in Telecommunication Engineering and a Master of Science in Information and Communication Technologies from the Universitat Politècnica de Catalunya, Spain, in 2008. He received his Ph.D. in Electrical and Computer Engineering from the Georgia Institute of Technology, Atlanta, GA, in August 2013. His research interests are in terahertz communication networks, wireless nano-bio-communication networks, and the Internet of Nano-Things. In these areas, he has co-authored more than 250 peer-reviewed scientific publications, including one book, and has been granted five patents. His work has received over 16,000 citations (h-index of 58 as of November 2023). He is serving as the lead PI on multiple grants from U.S. federal agencies, including the National Science Foundation, the Air Force Office of Scientific Research and the Air Force Research Laboratory, and industry. He is the recipient of multiple awards, including the 2017 IEEE ComSoc Young Professional Best Innovation Award, the 2017 ACM NanoCom Outstanding Milestone Award, the NSF CAREER Award in 2019, the 2022 IEEE ComSoc RCC Early Achievement Award, and the 2022 IEEE Wireless Communications Technical Committee Outstanding Young Researcher Award, among others, as well as six best paper awards. He is a Fellow of the IEEE (Class of 2024) and an IEEE ComSoc Distinguished Lecturer (Class of 2022-2023). He is also the Editor in Chief of the Elsevier Nano Communication Networks journal and Editor for IEEE Transactions on Communications and Scientific Reports.