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TCCN Newsletter

Vol. 7, No. 1, March 2021

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Chair's Message

Dear TCCN Fellow Members,

I hope that you, your loved ones, and your colleagues are safe and well. I am very happy writing to you for the first time as the TCCN Chair in the Newsletter.

Firstly, I would like to express my sincere thanks to the 2019-2020 TCCN Chair, Prof. Yue Gao, and other TCCN officers for their enthusiastic support and services to the community. Together with our fellow TCCN members, we have achieved a number of milestones in the past two years such as recertification, awards, SIGs, etc. I am pleased to introduce the newly elected officers for 2021-2022:

- Chair: Dr. Lingyang Song, Peking University, China
- Vice-Chair Europe/Africa: Dr. R. Venkatesha Prasad, Delft University of Technology, Netherlands
- Vice-Chair Asia Pacific: Dr. Lin Gao, Harbin Institute of Technology, China
- Vice-Chair Americas: Prof. Shiwen Mao, Auburn University, USA
- Secretary: Dr. Yuan Ma, Shenzhen University, China

All elected officers have been very active in the TCCN community, and some of them have served in various TCCN leadership roles in the past few years.

We have also appointed several officers during the past few months, including:

- Standards Liaison: Dr. R. Venkatesha Prasad, Delft University of Technology, Netherland
- Publicity Board:
  Dr. Vijay Rao, Delft University of Technology, the Netherlands
  Dr. Hongliang Zhang, Princeton University, US
- Student Competition Program:
  Dr. Kaoru Ota, Muroran Institute of Technology, Japan
  Dr. Boya Di, Imperial College London, UK

The elected and appointed officers will work together with our members to serve TCCN community.

The TCCN Newsletter has become an important electronic platform for TCCN members to exchange research ideas and brainstorm about the future of the TC. Starting from next issue, TCCN Vice-Chair, Dr. Lin Gao, will serve as the Newsletter Director. There is no doubt that the Newsletter will be taken to the next level. Meanwhile, I would also like to sincerely thank Dr. Daniel Benevides da Costa, the former newsletter director, for his great efforts and excellent work.

We encourage more volunteers to actively engage in various aspects of the TC, including but not limited to:

- Organize Special Interest Groups (SIGs) (contact: Shiwen Mao)
- Organize Special Issues for the TCCN Newsletter (contact: Lin Gao)
- Contribute to the publicity efforts of TCCN (contact: Vijay Rao, Hongliang Zhang)
- Contribute to student competition program (contact: Kaoru Ota, Boya Di)
- Involve TCCN Free Virtual Seminar (contact: R. Venkatesha Prasad)
- Involve TCCN in Comsoc conference organization (contact: Lin Gao)
- Involve TCCN in Comsoc journal special issues (contact: Shiwen Mao)

As always, any suggestions from TCCN members are welcome regarding how to make TCCN a better community. Please feel free to contact me at lingyang.song@pku.edu.cn to drop your suggestions.

Thanks and best regards,

Lingyang Song, Fellow of IEEE
Chair, IEEE ComSoc TCCN
Peking University, China

Director's Message

While 5G is a reality and has already been commercially launched in several parts of the world, there exist already numerous efforts and initiatives from industry and academia to look beyond 5G and conceptualize 6G by describing its roadmap along with the emerging trends and requirements, as well as several enabling techniques and architectures. Future wireless systems should effectively support a universal and ubiquitous cyber physical structure, new spectrum access schemes, and new forms of communications, while taking into account the energy efficiency and security/privacy considerations.

Two promising technologies for enabling the 6G ecosystem are full-duplex (FD) communications and integrated space-air-terrestrial communication (ISATC) systems. In this regard, this Newsletter will delve on these two key technologies for 6G wireless networks. In the FD communications area, we have interviewed Mr. Kenneth Kolodziej, from MIT Lincoln Laboratory, USA, Prof. Ioannis Krikidis, from University of Cyprus, Cyprus, Prof. Özgür Gürbüz, from Sabanci University, Turkey, and Prof. Chan-Byoung Chae, from Yonsei University, South Korea. We have also had the pleasure to get two position papers written by Prof. Alexios Balatsoukas-Stimming, from Eindhoven University of Technology, Netherlands, and by Prof. Jeyanandh Paramesh, from Carnegie Mellon University, USA, Susnata Mondal, from Intel Inc., and Ahmed Alkhateeb, from Arizona State University, USA. Within the context of ISATC systems, we have interviewed Prof. Pei Xiao, from the University of Surrey, UK, Prof. Mohamed-Slim Alouini from King Abdullah University of Science and Technology, Saudi Arabia, and Prof. Jianping An, from Beijing Institute of Technology, China, who provided us with their outlook on the opportunities and challenges on the theme.

I would like to thank our two feature topic editors: Prof. Himal A. Suraweera, from University of Peradeniya, Sri Lanka, and Prof. Gaofeng Pang, from Beijing Institute of Technology, China, for their hard efforts in arranging the content of this Newsletter. Moreover, we want to thank all authors and interviewees for sharing with us their experience and time. I would finally like to acknowledge the gracious support from the previous TCCN Chair, Dr. Yue Gao, from the current TCCN Chair, Prof. Lingyang Song, and from all TCCN officers. If you have any suggestion, feel free to contact me at: danielbcosta@ieee.org. We hope that you enjoy the material of this Newsletter!

Daniel Benevides da Costa
Director, IEEE ComSoc TCCN Newsletter
National Yunlin University of Science and Technology, Taiwan
Federal University of Ceará, Brazil

Feature Topic: Full-Duplex Communications Editor: Himal A. Suraweera

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Achieving full-duplex capability has been the focus of a burgeoning body of research over the past decade. Full-duplex operation allows simultaneous signal transmission and reception on the same channel; thereby it has the potential to double the spectral efficiency as compared with conventional half-duplex mode. Full-duplex operation also promises latency improvements, efficient collision detection protocols and hidden node elimination.

Practical full-duplex radio designs need to overcome the self-interference (SI) issue. When trying to receive signals while transmitting at the same time, a large power leakage can overwhelm the receiver front end circuitry. Therefore, SI should be sufficiently suppressed up to the noise level to enable FD operation. This can be achieved using passive/propagation, analog and digital domain cancellation techniques in the FD transceiver. Furthermore, use of multiple antennas allows spatial domain SI suppression solutions to be deployed effectively. FD transceivers in future wireless systems are expected to adopt a combination of above SI cancellation techniques characterized by low computational complexity and reduced power consumption.

Although much on 6G is still premature, some anticipated use cases are expected to benefit from FD communications. These include applications such as virtual/augmented reality that demand ultra-low latency and very high throughput. FD can also serve as a complementary method to massive MIMO in future wireless networks. To this end, despite the challenges posed by wide bandwidths and hardware nonlinearities, realization of millimeter wave FD transceiver systems have made significant progress as evidenced from the recent literature. Moreover, FD capable radios will open up new use cases and IoT applications that require simultaneous sensing and transmission, uplink/downlink transmission for computation and information transfer at the same time, and simultaneous information and power transfer in upcoming wireless networks.

In this feature topic of full-duplex communications, we will report some of the latest advancements in the field. We present two position papers and four interviews conducted with leading experts of the field. Due to their vast experience and visionary views on the topic, we are able to report the state-of-the art, potential uses, and open challenges of FD communications comprehensively. The first position paper by Prof. Alexios Balatsoukas-Stimming (Eindhoven University of Technology, Netherlands) describes applications of machine learning for non-linear SI suppression. The second position paper by Prof. Jeyanandh Paramesh (Carnegie Mellon University, USA), Susnata Mondal (Intel Inc.) and Ahmed Alkhateeb (Arizona State University, USA) describes the challenges and opportunities of millimeter wave FD transceivers. The four interviews from Mr. Kenneth Kolodziej (MIT Lincoln Laboratory, USA), Prof. Ioannis Krikidis (University of Cyprus, Cyprus), Prof. Özgür Gürbüz (Sabanci University, Turkey) and Prof. Chan-Byoung Chae (Yonsei University, South Korea) share expert views and insights on various topics of FD. We hope that the contents of this feature topic will inspire academia and industry to further devote their efforts to push FD technology one step closer to maturity.

Himal A. Suraweera is currently a senior lecturer in the Department of Electrical and Electronic Engineering, University of Peradeniya, Sri Lanka. He is in the editorial boards of IEEE Transactions on Communications and Transactions on Green Communications and Networking. He was a co-recipient of the IEEE ComSoc Leonard G. Abraham Prize in 2017. His research interests include cooperative communications systems, full-duplex wireless techniques, energy harvesting communications, massive MIMO systems, and machine learning. He is a senior member of the IEEE.

Self-Interference Cancellation in Full-Duplex Radios: Is Machine Learning a Panacea?

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1. Introduction

In-band full-duplex communications have attracted a lot of interest in the research community since the first demonstrations of practical full-duplex systems almost 10 years ago [1] [2]. This fundamental re-thinking of the physical layer spurred significant interest in its implications for higher levels of the OSI model. For example, in a full-duplex system one can use carrier-sense multiple access with collision detection (CSMA/CD) for the medium access control (MAC) layer, since transmission and carrier sensing can take place simultaneously.

One of the fundamental challenges that full-duplex systems are faced with is the fact that simultaneous transmission and reception results in a very strong *self-interference* (SI) signal. For a full-duplex system to work, this SI signal needs to be cancelled. The amount of the required SI cancellation depends on the application. For example, if full-duplex is used to enable CSMA/CD on the MAC layer or if it used to detect the transmission of primary users in cognitive radios, then perfect SI cancellation may not be required since in these scenarios it is typically sufficient to detect the presence of another signal without demodulating it. On the other hand, if full-duplex is used to enable simultaneous in-band bi-directional communication to double a system’s spectral efficiency, then the SI signal needs to be cancelled down to the level of the receiver noise floor to avoid any performance degradation.

SI cancellation is carried out in multiple steps: 1) passive isolation, 2) active analog cancellation, 3) active digital cancellation. The goal of active digital cancellation is to remove any residual SI from the remaining two SI cancellation steps using digital signal processing (DSP) techniques. However, due to non-linear effects that are introduced by the transceiver chain, high-complexity non-linear DSP techniques are usually required. These non-linear techniques traditionally rely on polynomial models, which are typically special (and lower complexity) cases of the Volterra series.

Recently, there has been a resurgence in the use of machine learning (ML) for signal processing and communications. ML is particularly interesting for non-linear signal processing applications, where traditional models can quickly become intractable.

In this paper, I will describe some recent applications of machine learning for non-linear SI cancellation. In doing so, I will make a conscious attempt to mention not only their strengths, but also their weaknesses. Finally, I will outline some open problems that pertain either to the ML techniques themselves or to new 6G-oriented avenues where ML could be useful in the context of full-duplex radios.

2. Full-Duplex Radios

A simplified block diagram of a typical full-duplex transceiver is shown in Figure 1. The transmitted digital baseband signal is first converted to an analog system using a digital-to-analog converter. The resulting signal is then upconverted to the carrier frequency by the IQ mixer and amplified by a power amplifier (PA). Finally, a bandpass (BP) filter is used to filter out any out-of-band emissions. Since the receiver is operating at the same time as the transmitter and on the same frequency band, a strong echo of the transmitted signal is received, which forms the SI signal. Note that, while Figure 1 shows a two-antenna system, there are many other possible architectures for the antenna front-end (e.g., using a circulator). The SI signal may be

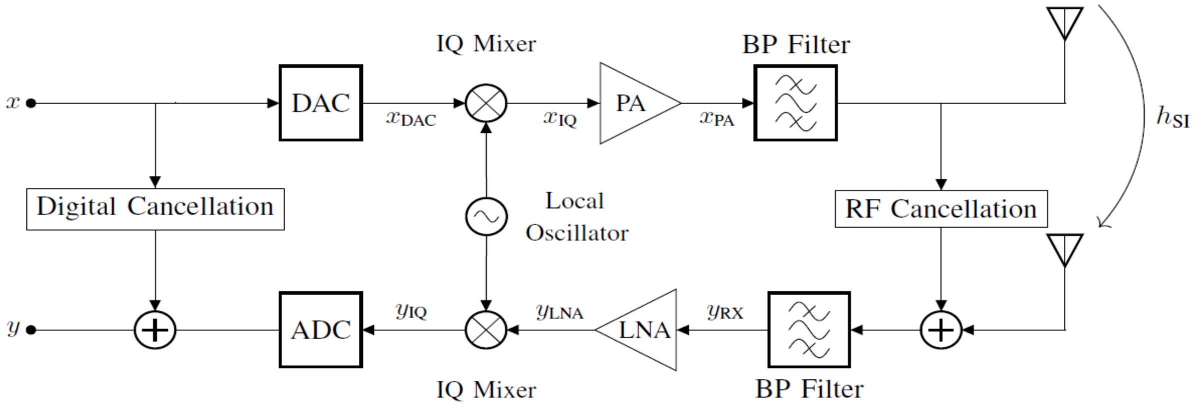

Figure 1 Block diagram of a full-duplex transceiver with active RF SI cancellation and digital SI cancellation (some components have been omitted for simplicity) **[4]**.

partially cancelled by an active RF canceller, but some residual SI typically makes its way to the downconverted and digitized received baseband signal. The goal of digital SI cancellation is to reconstruct the residual SI signal based on the transmitted baseband signal and to subtract the reproduced SI signal from the received signal.

The active components (e.g., DAC, IQ mixer, PA) of the transceiver chain introduce non-linear effects into the received SI signal. As such, non-linear models have to be used to reconstruct it. A commonly used model is a modification of the *parallel Hammerstein* model, which is a special case of the Volterra series and can naturally capture memory effects, IQ mixer non-linearities, and PA non-linearities. This model often serves as the baseline for comparisons with machine learning methods.

3. Machine Learning for Digital SI Cancellation in Full-Duplex Radios

The modified parallel Hammerstein model works well in practice, but it has certain limitations, which are outlined below.

- Its complexity grows quickly as the non-linearity order increases. This is an issue because PAs are typically operated in their non-linear regime where they are most energy efficient, but also introduce the most non-linear effects. This is also an issue for future THz and optical systems, where these non-linearities may be more pronounced.
- When re-writing the model so that it is linear in its parameters and can be trained efficiently, the model becomes overparameterized in the sense that it contains many synthetic parameters that are in principle correlated but are treated as uncorrelated for the purposes of training. As such, training can become difficult and the complexity of the model is needlessly high.
- As a model-based approach, it is inherently limited in terms of the non-linearities that can be represented.

For these reasons, many researchers have recently started exploring the use of data-driven ML approaches for SI cancellation. Note that, while in this paper I only discuss SI cancellation, similar techniques can be applied to other non-linear signal processing problems (e.g., digital predistortion).

Black Box Neural Networks

One of the first works to explore the use of ML-based methods for SI cancellation in the recent literature was [3]. This work uses a very simple feedforward neural network (NN) to replace the non-linear components of the modified parallel Hammerstein SI canceller, while linear cancellation is performed by a standard linear SI canceller. Performing linear cancellation first was shown to drastically improve the total achievable SI cancellation performance, as it makes training significantly easier. This approach also reduces the dynamic range of the NN inputs, which means that a lower quantization bit-width is required when implementing the NN canceller in hardware [4]. The power spectral density (PSD) of the SI signal after various stages of cancellation is shown in Figure 2. We observe that the NN SI canceller achieves the same performance as the polynomial canceller, and it was shown in [3] that the NN canceller requires approximately 40% fewer multiplications to achieve this performance. The follow-up work of [5] explored more advanced NN structures, such as recursive NNs and complex-valued NNs. All NN architectures were able to achieve similar SI cancellation results, but a complex-valued feedforward NN had the lowest computational and memory complexity. Unfortunately, while these results are useful from a practical perspective, as is common with black-box approaches, they offer little insight into the essence of the problem.

Domain-Specific Neural Networks

There is a strong case for domain-specific (also called *model-based*) NNs in the field of communications. More specifically, the argument is that, if we exploit expert knowledge and find ways to integrate it into the NN structure, we can typically reduce the overall complexity of the system significantly. One very basic example of this is the use of linear SI cancellation before the NN SI cancellation in [3], but there are also more advanced applications of this idea. For example, the authors of [6] modify the structure of the NN by exploiting the fact that more recent samples of the transmitted signal play a more significant role in the SI signal than older samples. This observation allows them to prune many connections in the NN, which reduces the complexity significantly compared to the complex-valued NN canceller of [5]. The work of [7] follows a different approach to include expert knowledge in the NN. In particular, the authors use the concept of *deep unfolding* to unfold the equations of the modified parallel Hammerstein model and to represent it as a NN. This NN has significantly fewer parameters than a black-box NN and it also has the added advantage that these parameters have a physical interpretation (e.g., two parameters represent the amplitude and phase mismatch in the IQ mixer). This model-based NN can be trained using standard training tools for NNs. The results of [7] show that, for the same SI cancellation performance, the model-based NN has approximately 70% lower complexity than the complex-valued NN of [5]. However, the model-based NN converges slightly more slowly to a good solution than the complex-valued NN.

Full-Duplex MIMO Systems

The use of data-driven approaches becomes even more attractive when the system complexity increases, as this is the regime where traditional model-based approaches become impractical due to their high complexity. One example are full-duplex MIMO transceivers, where M transmit antennas cause SI to N receive antennas. It is possible to perform digital SI cancellation using N distinct SI cancellers that take into account the signal from all M transmit antennas, but this approach has a very high complexity. The work of [8] argues that there is significant correlation between the received SI signals at the M transmit antennas. It is difficult to capture this correlation with model-based approaches, but the authors propose an NN-based SI canceller with appropriate structure that is shown to perform well and with lower complexity than other approaches. One drawback of the work is that no measured data was used, although it is understandable that building a full-duplex MIMO testbed involves significant effort and cost. This approach becomes even more interesting if other effects are considered, such as pre-PA crosstalk.

Other Machine Learning Methods

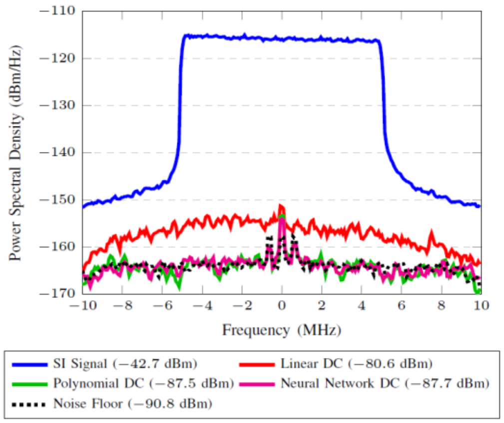

Figure 2 Power spectral densities of the SI signal, the SI signal after linear cancellation, as well as the SI signal after non-linear cancellation using the polynomial the NN cancellers **[3]**.

So far, we have only focused on NNs. However, any ML method that can perform non-linear regression is in principle suited for the task of non-linear SI cancellation. For example, the work of [9] uses support vector machines (SVMs) for SI cancellation in FDD transceivers. The authors show that this data-driven approach significantly outperforms a standard adaptive filtering approach over a wide range of frequency allocation and transmit power scenarios. The overall complexity for SVMs could be a practical limitation for this method, especially considering the fact that Gaussian kernels are typically used, which require the computation of exponentials that is relatively costly in hardware. The work of [10] explores the use of a low-rank tensor completion method for non-linear SI cancellation. This method achieves comparable SI cancellation performance with NN-based methods with marginally lower computational complexity. However, it has significantly more parameters and, thus, requires significantly more memory than NN-based methods.

4. Discussion and Open Questions

In this paper, we only mentioned some indicative works in the direction of using ML for SI cancellation to pique the curiosity of the readers of this newsletter. There are many other works and significant advances have been made in the past few years. However, there is also a large number of open questions and points of discussion, some of which are outlined in the remainder of this section.

Alternative Non-linear Regression Methods

First of all, there is a plethora of data-driven ML methods that can perform non-linear regression and only a few have been explored so far. While improving the most common structures, like NNs, is certainly useful, larger gains may be obtained by finding the most appropriate technique for each considered scenario. As discussed previously, the integration of expert knowledge into the structure of NN-based SI cancellers is very beneficial and an essential aspect to the success of alternative ML methods is the integration of such expert knowledge. Contrary to NNs where this can be achieved in a relatively natural way, it is still unclear how this integration can be carried out for other ML approaches.

Training Complexity

Practically all existing works contain some form of complexity comparison between their proposed methods and some baseline method. However, this comparison is almost exclusively done for the inference step. Since inference is performed for every sample in SI cancellers, this is a very natural starting point. However, both the non-linear transceiver effects and the SI channel change over time and some form of re-training is necessary in full-duplex systems. As such, it is essential to carefully compare the training complexity of the various data-driven ML approaches that have been proposed in the literature. The training methods are often vastly different in terms of the computations that are involved, so making a fair comparison is far from straightforward. One possible way to reduce the (re)training complexity is to use methods that can separate the slowly varying components (e.g., the changes in the PA due to temperature) from the more quickly varying components (e.g., the SI channel) so that the corresponding parts of the ML solution can be re-trained separately.

Datasets and Source Code

I have made it standard practice to make both the dataset and the source code of the works I am involved with in this area publicly available. While some other authors also release their datasets and source code (e.g., [6]), this is far from common practice. This situation is unfortunate as it makes reproducibility and fair comparisons difficult, while also hindering progress. I believe we should follow the open paradigm of the machine learning community much more closely.

Hardware Implementations

Complexity analyses that measure additions, multiplications, and other operations are a useful high-level tool to compare different ML approaches for SI cancellation. However, they do not capture all aspects of the complexity of each ML method. Important issues, such as quantization, parallelizability, and memory access patterns can only be assessed through actual hardware implementations.

Beyond-5G Systems

Some of the envisioned properties and solutions for beyond-5G systems align particularly well with the trend of using ML for SI cancellation. For example, using standard NNs for this task (as well as other transceiver tasks) is beneficial for cloud radio access networks (C-RANs), as common and massively produced computational platforms (e.g., a GPUs or TPUs) can be shared to perform multiple tasks. Moreover, the predicted trend towards higher frequency bands (e.g., THz and optical bands) will require transmitter non-linearity compensation, which can be carried out jointly with SI cancellation in corresponding ML-based full-duplex systems. Finally, the push for even larger massive MIMO (and holographic MIMO) systems will most likely make traditional SI methods completely infeasible, giving an additional edge to ML-based methods.

5. Conclusion

The main takeaway from the discussion on this paper is that the jury is still out on the question whether machine learning is a panacea for SI cancellation in full-duplex systems. I find this conclusion rather exciting, as it means that there are challenges left to address and we can expect to see many more interesting works in this direction.

Alexios Balatsoukas-Stimming is currently an Assistant Professor at the Eindhoven University of Technology in the Netherlands and an Adjunct Assistant Professor at Rice University in the USA. He received the Diploma and MSc degrees in Electronics and Computer Engineering from the Technical University of Crete, Chania, Greece, in 2010 and 2012, respectively, and a PhD in Computer and Communications Sciences from the École polytechnique fédérale de Lausanne (EPFL), Switzerland, in 2016. He then spent one year at the European Laboratory for Particle Physics (CERN) as a Marie Skłodowska-Curie postdoctoral fellow and he was a postdoctoral researcher in the Telecommunications Circuits Laboratory at EPFL from 2018 to 2019. His research interests include VLSI circuits for communications, error correction coding theory and practice, as well as applications of approximate computing and machine learning to signal processing for communications.

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Millimeter-Wave Full-Duplex MIMO Transceivers: Challenges and Opportunities

Jeyanandh Paramesh[1], Susnata Mondal[1,2], and Ahmed Alkhateeb[3]

[1] Carnegie Mellon University, [2] Intel Inc., [3]Arizona State University

1. Abstract

In-band full-duplex signal can conceptually halve spectral needs for the same network throughput. Full-duplex, which has long been ignored due to the insurmountable obstacle of co-channel self-interference, has attracted renewed research focus in the last decade. At the same time, it is clear that multiple-input-multiple-output (MIMO) communication will form a mainstay of future wireless networks. Full-duplex can, in principle, serve as a complementary method to MIMO to enhance future wireless networks. This article describes challenges and research opportunities in the pursuit of developing networks that marry full-duplex with MIMO.

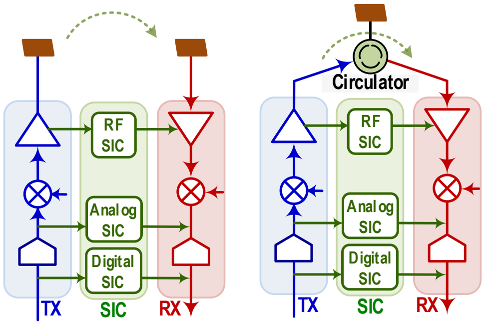
2. Introduction

A great deal of research and development has been conducted over the last decade to achieve order-of-magnitude increases in data rate, network capacity and user density in wireless networks. Two key approaches are being pursued towards this goal. First, new frequency bands below 6 GHz and in the upper microwave and millimeter-wave bands have been opened for commercial use. Second, new wireless networks (5G and beyond) that make explicit use of the spatial domain via multi-input-multi-output (MIMO) signaling techniques are under development. “Massive” antenna arrays and associated beamforming transceivers, which are foundational technologies for MIMO communication below 6 GHz and also in the mm-wave bands, are beginning to gain traction with the initial deployments of 5G networks.

Emerging wireless standards include time-domain duplexing (TDD) and frequency-domain duplexing (FDD) [1]. Hardware supporting TDD and FDD is commercially available below 6 GHz, while TDD hardware is available in the mm-wave bands. In terms of implementation difficulty, TDD systems are attractive since they inherently offer transmit-receive isolation. On the other hand, FDD systems face greater implementation challenges. This is because the transmitter and the receiver are simultaneously on and so FDD operation relies on having highly selective RF filters to isolate the (weak) receive signal at a radio node from its (strong) transmit signal.

Although obvious, it should be noted explicitly that neither TDD nor FDD provides direct increases in data rate or throughput. In contrast, in-band full-duplex signaling [2-4] can conceptually reduce the spectrum required for the same throughput, or conversely, double the throughput in the same spectrum. Also, full-duplex can reduce radio resource allocation overheads, thereby improving network throughput and latency. Moreover, full-duplex can be a complementary approach to MIMO, which is certain to be a key technological element in the pursuit of higher data rate, throughput and density in future networks [5-7]. Doubling the rate (or halving the resources) with full-duplex could be especially attractive in mm-wave channels which due to their sparse nature may not offer high spatial multiplexing gain. Enabling full-duplex MIMO, especially in mm-wave architectures, has also clear potential for allowing the coexistence of communication and radar functions in vehicular and autonomous systems. Accordingly, we think that the next frontier of wireless networks will aim towards the marriage of full-duplex and MIMO.

The realization of full-duplex MIMO systems critically depends on solving numerous open hardware and algorithmic challenges. The primary obstacle to full-duplex is the presence of co-channel self-interference (SI) from the transmitter into the collocated receiver. Over 100 dB of SI suppression may be required in practical systems. In single antenna systems, this level of suppression has to be achieved by combination of *isolation* of the received signal from the SI, and by *cancellation* wherein weighted and/or filtered replicas of the transmit signal are injected at several points along the receive chain. In MIMO systems, while both isolation and cancellation must be leveraged, it is



(a) (b)

Fig. 1. (a) Shared-antenna STAR system. (b) Separate-antenna STAR system.

possible to achieve additional SI suppression by means of *spatial* filtering. It should be noted that SI suppression using cancellation and spatial filtering should be performed *adaptively*. This is because the level of SI suppression required in practice changes dynamically as the radio environment changes. Adding SI suppression measures can degrade receiver performance, and such degradation should be dynamically minimized depending on the SI level. The remainder of this paper discusses implementation challenges that we expect to encounter in the pursuit of combining full-duplex signaling with MIMO.

3. Self-interference Isolation in Full-Duplex

There are two approaches to isolate the received (RX) signal from the transmit (TX) signal interference in full-duplex transceivers. The first is to use separate antennas for the TX and the RX paths [Fig. 1(a)]. The second employs a single shared antenna with a circulator that provides port isolation [Fig. 1(b)]. The design of circulators has attracted intense high research interest recently; however, they suffer from numerous shortcomings. First, they suffer from limited isolation, linearity, limited bandwidth and large size (or large die area, in recent chip implementations). Consequently, they are difficult to integrate into a multi-antenna system comprising a large number of elements. Second, circulators (especially those at mm-wave frequencies) [8] incur high insertion loss (> 3 dB) in both the TX and RX paths. This implies that while an ideal shared-antenna full-duplex system using a lossless circulator would require half the antenna aperture for identical link margin compared to a separate-antenna system, this advantage would effectively vanish in a realistic implementation using a lossy circulator having 3 dB loss. Third, conventional circulators are not useful in a shared-antenna MIMO system. This is because circulators in each element would isolate transmit and receive signals for that element, but would provide no isolation for the transmit leakage from adjacent antennas in a closely packed MIMO array. In contrast, leakage due to antenna coupling can be greatly reduced in a separate antenna approach by physically separating TX and RX array. This is the determining factor that favors separate antenna arrays in for full-duplex MIMO.

4. Full-Duplex + MIMO

A. MIMO Transceiver Architectures: Digital vs Hybrid

Digital MIMO transceivers offer *per element* digital interfaces between the signal processing engine and the antenna array. While this comes at a high price in terms of size, power and cost, digital MIMO transceivers offer high algorithmic flexibility for spatio-temporal processing, which is further aided by the cost and energy reduction benefits of Moore’s Law. On the other hand, hybrid MIMO transceivers offer *per stream* digital interfaces between the signal processing engine and the antenna array. Since the number of elements far exceeds the number of streams, hybrid architectures offer significant size, power and cost savings over fully digital MIMO architectures. In recent years, numerous papers reporting on MIMO algorithms that are cognizant of the hybrid MIMO architectural constraints have appeared. Such papers often assume –incorrectly in our opinion– that digital architectures will remain infeasible. Our position is that “enterprise” network-side hardware will eventually employ digital architectures since constraints on size, weight and cost constraints are not severe, while hybrid architectures will be attractive in user/mobile side hardware (and perhaps in low cost network-side hardware) where such constraints are extremely severe. While the development of large-scale MIMO architectures is in itself an area of high interest [9-12], our interest herein is that of introducing full-duplex functionality.

B. Full-duplex in Digital MIMO Architectures

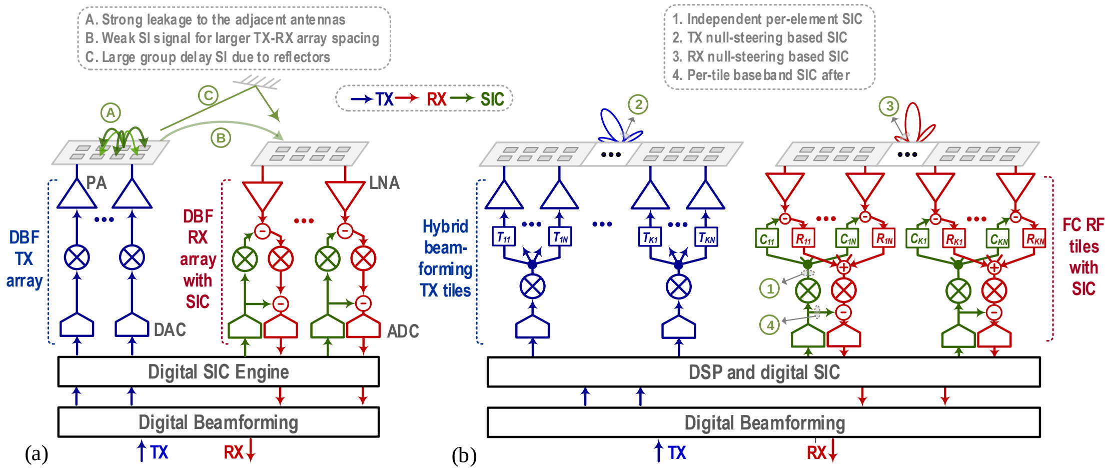


Fig. 1. Full-duplex MIMO architectures: (a) Digital architecture showing per element analog domain SIC. (b) Hybrid architecture using FC tile featuring per-element SIC. Both types will also have digital SI cancellation.

The discussion in Section II leads to the observation that a shared-antenna full-duplex MIMO requires multi-port circulator topologies that can isolate not only the receive path of a particular element from its own transmit signal, but also from the transmit paths of adjacent transmit signals. Such circulator topologies are not currently known. Therefore, we assume MIMO architectures that use separate transmit and receive arrays, which in turn are interfaced to separate transmit and receive electronics. In order to incorporate full-duplex into digital MIMO transceivers, the receiver must be architected such that it features several points along each receive chain where weighted/filtered copies of each transmit signal stream can be inserted in order to obtain progressively cancel SI. The SI cancellation signals can be generated by a digital SI engine. Accordingly, each frequency downconversion chain following each element in the receive array now effectively requires its own dedicated transmit and *up*conversion path to introduce the SI cancellation signals. An exemplary full-duplex MIMO architecture is shown in Fig. 2(a). Extrapolating from our recent MIMO prototype [12] which featured four bi-directional MIMO chains (and hybrid beamforming support for eight antenna elements) on a single chip, we posit that such an architecture is indeed feasible. Nevertheless, given that our prototype is one of the only known embodiments (if not the only one) of FD-MIMO transceivers to date, we posit that the design of FD-MIMO transceiver architectures as well as the high-performance SIC algorithms remains a wide-open area for future research.

C. Full-Duplex in Hybrid MIMO Architectures

We next present considerations of incorporating FD functionality into hybrid MIMO transceivers, which split the spatio-temporal processing (i.e., beamforming) into two parts, one implemented in the digital baseband domain and the other in the RF passband domain. In current parlance, hybrid MIMO architectures are assumed to be of the *partially-connected* (PC) type, where each input (output) of the digital baseband beamformer is frequency translated and interfaced (via *one* RF domain phase shifter per digital beamformer input/output) to a non-overlapping subset of elements in the receive (transmit) antenna array. More generally, a hybrid MIMO architecture may use *fully-connected* (FC) tiles, where each input (output) of the digital beamformer is frequency translated and interfaced (via multiple independent RF domain phase shifters per digital beamformer input/output) to an overlapping subset of elements in the receive (transmit) array. The former has the advantage of simplicity since it requires an independent phased array per stream, but the latter makes more efficient use of the aperture, which in turn enables better energy and spectral efficiency.

We presented these concepts and reported on the first FC-type hybrid MIMO chipscale prototypes in the literature in [9-12]. In [11] we showed that if the signal path from a given digital beamformer input/output to an antenna element were designed to be bi-directional, FD functionality would be inherently available along with *per element* and *per stream* SIC. In other words, multiple MIMO streams can be received while having SI cancellation. It is important to note a hybrid MIMO transceiver using FC tiles can support both MIMO and FD with SI cancellation, while a PC tile-based architecture which can support only MIMO.

While the 8-element/4-path chipscale FD-MIMO transceiver described in [12] demonstrates feasibility, much work remains to be done before FD-MIMO can achieve widespread acceptance. In particular: (1) enabling TX side MIMO still would require RX FC tile with more than two-streams. (2) Scaling up the number of output streams in the FC tile poses significant implementation challenges and can be a potential topic of future research. (3) It would also be interesting to investigate ways to increase TX-MIMO supported streams and corresponding RX array cancellation mechanism without physically increasing independent multiple SIC paths for each element.

5. Self-interference Suppression Methods

Signal Cancellation: As shown in Fig. 2(a), the transmit SI corrupts the received signal through *leakage* between the antenna elements, the printed circuit board and the chip substrate; and through *reflections* from objects in the vicinity of the radio. Leakage can be modeled by a single complex valued tap while the latter requires multiple complex valued taps arriving at different epochs from different directions. In practice, leakage generally has much higher magnitude and must therefore be canceled adequately in the front-end of the receiver in order to avoid saturating downstream circuits. In order to perform such cancellation, an upconverted version of the baseband transmit signal must be scaled by a complex weight and injected into an appropriate point in the receive chain, for example, in between the stages of the low-noise amplifier. In a FD MIMO receiver, it would be necessary to inject cancellation signals on a *per element* and *per stream* basis.

The design of single tap cancellation circuits in the RF front-end poses difficult challenges, especially in the MIMO case. Resolution, precision and cost are key considerations. Unlike conventional phased arrays that can work well even with low resolution constant modulus phase shifters, SI cancellation circuits require fine grained amplitude and phase control. Moreover, noise and non-linearity generated by the cancellation circuits should cause minimal corruption of the received signal. The cancellation circuitry must be extremely compact since it must be replicated for each element in a large array. Finally, random variations of the cancellation circuits that can lead to imprecise weighting and poor cancellation must be mitigated. We believe that these characteristics can be simultaneously achieved only by a combination of creative circuit implementation and large-scale integration in a modern semiconductor technology.

The residual SI that remains after leakage has been (partially) cancelled can be cancelled downstream along the receiver chain, as shown in Fig. 2(a-b). In principle, such cancellation requires multi-tap cancellers which can be implemented as digital domain FIR filters (or as single-tap cancellers following an FFT for OFDM signals). However, deferring this cancellation to the digital back end of the receiver may not be feasible since the SI may cause saturation earlier in the chain. Therefore, it may be necessary to investigate FIR filter-type cancellers in the analog baseband domain. The design and optimization of such circuits remains an open area of research. It should also be noted that tapped-delay line filters can perform cancellation on the RF passband signal (e.g., [13]). However, such circuits tend to be large and lossy, and may be impractical for FD-MIMO.

Spatial Filtering: In FD-MIMO systems, it may be possible to exploit spatial filtering to suppress transmit SI, since the SI is likely to arrive from a different direction than the desired signal. This method is complementary to the signal cancellation method described above. In digital MIMO architectures, generalized multi-tap (or FFT based) beamformer based SI cancellers can be implemented in the digital domain, which can in principle suppress multiple SI signals arriving from different directions. It will be then interesting to design beamforming approaches that jointly maximize the achievable rates while aiding the SI cancellation. Such cancellation method, in principle, do not suffer from bandwidth limitations. However, such suppression is possible only if the SI does not cause circuit saturation prior to beamforming. In hybrid architectures, on the other hand, multiple SI signals arriving from different directions can be cancelled by the front-end beamforming; however, since the RF domain beamforming typically has a single tap per element per stream, the achievable SI suppression degrades with increasing bandwidth. Nevertheless, front-end spatial filtering eases the requirements on the suppression required in the digital beamforming back end.

Adaptation for signal cancellation: Digital MIMO architectures [Fig. 2(a)] offer complete digital observability of the received signals after SIC as well as digital controllability of the cancellation signals on a per-element basis. Therefore, a wide variety of full-duplex SIC weight adaptation algorithms can be implemented targeting fast convergence and high cancellation. However, digital array computations have high power consumption and latency, which imposes practical constraints on the choice of SIC algorithms. Therefore, the design of energy-efficient full-duplex algorithms brings forth exciting opportunities for future research.

In a hybrid beamformer, digital outputs are available only after RF beamforming in each tile. Hence, a digitized receive signal and the residual TX leakage information (after per element RF domain cancellation) from each RX element are not available to the digital adaptation engine, which makes. many conventional beam-weight and SIC-weight adaptation techniques infeasible. Therefore, adaptation schemes that are cognizant of structural hardware constraints are of high interest. Some solutions are described and experimentally demonstrated in a mm-wave MIMO chipscale prototypes in our recent body of work. In [10], a time-multiplexed adaptation scheme is proposed that performs beam and null steering in a hybrid beamformer by using digitized data-stream outputs from the RF beamformer. This algorithm can also be used to direct nulls towards TX self-interference. In [12], a per element SIC weight adaptation scheme is demonstrated in a hybrid beamformer; this scheme performs time-multiplexed error-extraction and thus minimizes SI for each element. While these works show the feasibility of minimum-mean-square-error SIC adaptation in FD beamformers with per stream digitization only, the development of fast, robust, energy-efficient and hardware-aware adaptation algorithms for FD MIMO architectures remains a wide open area for future research.

6. Leveraging Machine/Deep Learning Tools

There are several venues where machine/deep learning can play important roles in enabling FD mm-wave MIMO systems. For example, machine/deep learning tools have powerful capabilities in learning complex and unknown models. Such capability can be leveraged to learn/model the complex near-field antenna array coupling and proactively predict/cancel the SI that may result in from this coupling. It can also be leveraged to learn the hard-to-model RF circuits of the hybrid architectures. Further, learning from prior observations, the machine/deep learning models may need only limited information about the transmit signal, the circuit, and the environment to make important SI predictions. This has the potential of reducing the training time/latency, the overhead on the resources, and the hardware complexity. Another important use case of machine/deep learning is enabling efficient adaptive beamforming for SI cancellation. In our prior work [14], we showed how deep learning approaches, such as self-supervised learning and reinforcement learning, can be efficiently used to learn and optimize the beam patterns of the mmWave phased arrays without requiring any knowledge of the array geometry or its non-idealities. These approaches can be extended to mm-wave FD-MIMO systems to optimize the beamforming weights to jointly minimize the SI signal and maximize the system achievable rates. The development and evaluation of these machine learning based full-duplex solutions can make use of the publicly-available channel datasets such as DeepMIMO [15], which has been used to evaluate several beamforming/channel estimation tasks in MIMO systems.

7. Conclusion

Massive MIMO has already begun to take hold in next generation wireless networks. Full-duplex signaling can potentially double spectral efficiency, but its introduction into MIMO networks presents challenges. This paper has attempted to describe some of these challenges, initial solutions by the authors’ groups and opportunities for future research at the physical layer.

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Interview with Kenneth E. Kolodziej

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Q1: Summary of your research, so far what are the important results obtained?

A1: My research on in-band full-duplex (IBFD) started in 2010 when I joined MIT Lincoln Laboratory. Since then, I have focused on demonstrating novel systems and self-interference cancellation (SIC) techniques, particularly in the propagation and analog/RF domains. Specifically, our group has combined high-isolation antennas, multi-tap RF cancellation and adaptive transmit beamforming methods to provide more than 100 dB of total isolation on a moving vehicle [1]. Additionally, we have increased the instantaneous bandwidth capability of analog cancellers to 1 GHz with the help of photonic components [2] as well as designed an all-digital IBFD aperture-level phased array architecture that measured more than 140 dB of transmit-receive isolation [3].

Most recently, I have had the honor of working with IBFD experts around the world to create a unique reference book, titled "In-Band Full-Duplex Wireless Systems Handbook" [4]. This collection of chapters from leading researchers covers SIC techniques that span all transceiver domains as well as their deployment by presenting the fundamentals, practical aspects and state-of-the-art results for IBFD wireless systems. It promises to introduce beginners to the field as well as support seasoned professionals in the development of IBFD technology for the future.

Q2: Can you explain the self-interference problem? Summarize worldwide efforts and progress so far to solve the SI issue (propagation / analog / digital / spatial domain SI cancellation).

A2: One of the significant challenges for any wireless system is dealing with interference, which is traditionally generated by other users. IBFD systems, however, are different in that they also must contend with self-interference (SI) that is created by the co-located transmitter, which is active at the same time and tuned to the same band as the receiver. If untreated, this SI can easily saturate or damage the receiver electronics, and additionally produce unwanted nonlinear distortions within the band, which can degrade system performance.

Research on SIC techniques has spanned the propagation, analog and digital domains of an IBFD transceiver, where successful systems have carefully integrated multiple methods across these domains. A detailed list and discussion of worldwide-published SIC techniques as well as the performance of 100+ measured IBFD systems has been collected in [4] and [5]. These survey works indicate that while employing SI reduction methodologies in the propagation and analog domains can help protect receiver components, it is the incorporation of digital-domain filtering that enables the highest-performing IBFD systems. This is evident in [6], where 115.3 dB of total SI isolation was measured for a system that implemented cancellation across all three domains for an IBFD relay application.

Q3: Full-duplex has been proposed for a variety of use cases such as: simultaneous spectrum sensing and communication for cognitive radio applications, fast channel estimation, simultaneous transmission and jamming for physical layer security, uplink/downlink transmission for simultaneous computation and communication etc. What needs to be done so that they could be adopted in practice?

A3: As part of the IBFD community, we have to work to mature both the individual and system-level technologies by moving from scientific investigations towards practical research and development for these specific areas. While there has been a vast amount of articles published on IBFD system simulations, particularly at the higher networking layers, there are relatively few that include results of measured prototypes, many of which are restricted to laboratory operation only. By advancing the robustness and reducing the size, weight and power of the physical-layer hardware, firmware and software, practical IBFD devices can be produced. With these in hand, research on the interactions among multiple users as well as the performance in a given application scenario can be conducted to understand the best path forward to integrating IBFD into a wireless standard.

Q4: Despite many years of significant theoretical and experimental work, full-duplex is not considered for 5G, What are the reasons? Will this change? What would be the first FD indoor / outdoor applications that could emerge?

A4: Similar to the above, many aspects of IBFD wireless technology are not yet mature enough for inclusion within a communication standard, such as 5G. Medium- to large-scale demonstrations of IBFD networking between users and base stations would be a tremendous achievement to validate the years of research on SIC techniques and prototype systems in the laboratory. Even if that success was quickly realized, I do not think that IBFD will be incorporated into the 5G specification for two reasons. Firstly, 5G promises to introduce many new features, including wider channel bandwidths and millimeter wave (mmW) operation, both of which will require performance optimization as well as the attention of device designers and networking engineers. Secondly, planning for the 6G wireless standard and commercialization is already underway, and would present a more realistic opportunity for the inclusion of IBFD technology if the readiness is validated as mentioned.

Regarding the first applications to emerge, I would say that scenarios with relatively constant SI channels offer a lower barrier to entry since the dynamic adaptation and associated processing requirements are greatly relaxed. Examples of such applications include outdoor point-to-point wireless relays and microwave backhaul links.

Q5: Could you talk a bit on wired FD standards such as DOCSIS, G.mgfast etc. What are the challenges / what are the differences as compared to wireless? How far standardization has progressed?

A5: I should start by emphasizing the fact that my research has solely been on the wireless side of IBFD, and that I am not as familiar with wireline applications. With that said, I understand that these systems are also interested in increasing their throughput or bandwidth without adding additional cables to the network, for which IBFD technology can help. While the concepts and potential efficiency gains are the same between wireless and wireline networks, the latter offers the distinct advantage of working in environments with fairly well-controlled SI channels, i.e. reflections are generated and contained within the cables themselves. This does not mean that the wired IBFD implementation is easy, and therefore, it is a great accomplishment for the IBFD field to see this capability be successfully adopted into these standards.

Q6: How critical is upper layer design so that gains promised by full-duplex can be reaped? Are there any performance bounds, new theory to be developed? What are the practical issues?

A6: As mentioned above, I have been focused on physical-layer techniques and systems in my work. While I still think we have a way to go improving the base hardware capability and robustness, I feel that the upper-layer design is critical to guarantee the success of IBFD. This comes back to the idea of needing to conduct significant real-world demonstrations to illustrate the maturity of the technology. I am sure that there are many practical issues to overcome, and one of the most interesting is to determine the optimal method of networking between IBFD-capable and traditional devices that have historically avoided excess transmissions along with the external interference that is generated.

Q7: Full-duplex is touted to implement 6G. What are the “anticipated” 6G applications that could benefit from FD operation? Do you think FD will play a complementary role for mmWave and THz communication systems? What path would device manufacturers, service operators would take?

A7: While much of 6G is still to be determined, it seems to promise that "everything" will become connected to the internet, such that objects, devices and people will be networked together. Many of these connections, however, only require sporadic communications and would thus not benefit from incorporating IBFD technology. One of the exceptions to this is extended reality (XR) that encompasses the areas of virtual/augmented reality, and merges the physical and virtual worlds. This application necessitates high data throughput and low latency, which could make it a great candidate for IBFD operation.

As evidenced by existing research, IBFD can be applied at mmW and THz frequencies [7]. Since these relatively high frequency systems are often directional in nature, I do not see IBFD making as much of an impact as in the sub-6 GHz bands, where spectrum allocations are much more scarce and expensive, but who knows – maybe that will change as 5G begins to bring more devices into those bands.

Q8: Machine learning and artificial intelligence technologies are increasingly used in wireless communications. What could they provide for SI cancellation / FD implementation / FD applications? How will they complement signal processing and radio implementation in FD transceivers? What are the challenges?

A8: The incorporation of machine learning (ML) in IBFD systems has already begun in the form of complexity reduction for nonlinear digital cancellation schemes [8] and analog canceller tuning speed acceleration [9]. Other than expanding on these cancellation techniques, ML and artificial intelligence (AI) will more than likely be incorporated into channel monitoring and associated band-allocation predictions to deliver on the promise of cognitive radio enabled by IBFD technology. While much research is required, one of the main challenges will be creating practical and efficient ML/AI training datasets and strategies to minimize the overhead associated with these features.

Q9: How lessons learned from self-interference cancellation in-band full-duplex communications can be applied to other scenarios (e.g., digital pre-distortion, adjacent channel leakage)?

A9: The origins of many SIC techniques for IBFD can be traced to other applications, and it only makes sense that some of these methods will in turn support areas that were not initially envisioned. For example, many military platforms operate multiple wireless systems/sensors at different frequencies (not with IBFD), but could utilize cancellation methods to mitigate the resulting co-site interference that plagues them. On the commercial side, analog/digital cancellation modules have been shown to reduce the hardware associated with traditional radio front-ends and provide for more efficient use of adjacent channels [10]. While these are only two example use-cases, I would expect more to emerge in the future.

Q10: In your view what are the key outstanding issues remain to be solved so that FD could become a ubiquitous technology used in wireless and wired systems?

A10: Initial research on IBFD techniques and systems should look to expand the operational frequency range and instantaneous bandwidth capabilities as well as increase the transmit output power to produce evidence that this technology can be applied to a wide host of locations and applications. As previously mentioned, additional investigations should be conducted to mature the individual methods before feeding into a multi-device network demonstration that includes upper-layer integration. Finally, the leading experts in their respective areas of IBFD have shared their opinions on the future direction of the field in the aforementioned handbook, which promises to help IBFD become a mainstream technology in the future [4].

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Interview with Prof. Ioannis Krikidis

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Q1: Summary of your research, so far what are the important results obtained?

Since the beginning of my PhD studies, I have specialized in wireless systems and acquired a wide range of technical skills in wireless communication theory, signal processing, and performance analysis, and have successfully applied these tools to various wireless network design problems. In 2018, I founded the IRIDA Research Centre for Communications Technologies at the Department of Electrical and Computer Engineering of the University of Cyprus. The Centre's main focus is to conduct research in the broad area of communication theory, wireless communications and networks, with specific emphasis on the physical and medium access control layers. In a nutshell, we use mathematical tools to model, design and analyze emerging wireless communication systems, leading to innovative and/or theoretically optimal communication techniques. My research activities deal with multiple-antenna systems, cooperative networks, wireless powered communications, 5G/B5G wireless systems, and full-duplex (FD) radio.

FD radio is one of the main research topics of my team; I started working on this topic in early 2012. Our key contributions in this area consists of the design and analysis of cooperative networks with FD capabilities. In addition, we have studied the fundamental combination of FD relaying with wireless power transfer, where relays harvest radio-frequency signals to power the second-hop. Another major contribution was to consider FD radio as an advanced mechanism, in order to enhance physical-layer secrecy in wireless communications with eavesdropping (simultaneous transmission and jamming). Finally, we have studied the FD radio from a system level standpoint by considering cellular networks with spatial randomness where base stations/terminals operate in FD mode

Q2: Can you explain the self-interference problem? Summarize worldwide efforts and progress so far to solve the SI issue (propagation / analog / digital / spatial domain SI cancellation)

The main idea of FD communications is to allow a terminal to transmit and receive at the same time and over the same frequency band. However, this operation results in a signal leakage from the transmitting to its own receiving RF chain, causing self-interference (SI). Due to the short distance between the transmit and receive antennas at a terminal, the SI power is much stronger than that of the desired signal, compromising the ability of a node to decode the desired signal. To achieve the best performance of an FD system, researchers have focused on mechanisms to suppress the SI signal below the receiver's noise floor, either in the propagation, the analog or the digital domain.

In particular, propagation-based SI cancellation techniques aim to effectively separate the transmit and receive antennas through antenna directionality, cross-polarization, and by placing absorptive shielding between antennas. Moreover, SI cancellation schemes in the analog domain focus on suppressing the SI just before the analog-to-digital converter (ADC) by using both adaptive (e.g., Balun) and non-adaptive (e.g., QHx220 chip) SI cancellers. Finally, digital signal processing techniques cancel out the SI by applying sophisticated signal processing tools after the ADC, such as antenna beamforming, optimal power gain control and allocation, antenna selection, null-space projection, minimum mean square error (MMSE) filters, etc.

Q3: Full-duplex has been proposed for a variety of use cases such as: simultaneous spectrum sensing and communication for cognitive radio applications, fast channel estimation, simultaneous transmission and jamming for physical layer security, uplink/downlink transmission for simultaneous computation and communication etc. What needs to be done so that they could be adopted in practice?

Although FD technology has been thoroughly investigated in theory as well as in controlled laboratory environments, its implementation in real-world scenarios is still in its infancy. The practical implementation of FD radio technology introduces various technical challenges i.e., multi-tap and time-varying SI channel, non-linearities imposed by the circuits (e.g., from the power-amplifier), asymmetric data traffic, synchronization issues etc. In addition, FD implementation typically comes at the expense of added radio complexity, which implies higher cost and power consumption in comparison to existing conventional solutions. Therefore, the consideration of FD radio in future wireless systems requires further advances in the SI suppression mechanisms that take into account practical non-idealities as well as hardware implementations that significantly reduce computation/power/silicon area.

Q4: Despite many years of significant theoretical and experimental work, full-duplex is not considered for 5G, What are the reasons? Will this change? What would be the first FD indoor / outdoor applications that could emerge?

Although the initial technical discussions on 5G involved the employment of the FD technology, it has not been adopted in the current 5G Releases, mainly due to its immature investigation in real-world communication scenarios. In order for the FD technique to be successfully employed in future wireless systems, the challenges that exist at all the layers of the protocol stack need to be addressed. These range from the antenna and circuit design (e.g., due to hardware imperfection and non-linearity, the non-ideal frequency response of the circuits, phase noise, etc), to the development of new theoretical foundations for complex wireless networks with FD terminals. An additional challenge that needs to be overcome is the high-cost and huge power consumption of FD-enabled circuits with SI suppression capabilities above 100 dB. Fortunately, with the expected future technological advances and the maturity that the FD technology is likely to achieve in the next decade, the duplex mode in the B5G/6G era is expected to operate in FD mode.

Q5: Could you talk a bit on wired FD standards such as DOCSIS, G.mgfast etc. What are the challenges / what are the differences as compared to wireless? How far standardization has progressed?

FD technology is a promising solution to provide gigabit-class broadband access over legacy twisted pairs and coaxial cables. This aspect is very important, specifically for areas with low user density where fiber access installation is costly and/or infeasible. The FD technology is integrated in cable modems to support simultaneously uplink/downlink streams towards doubling the aggregate bit-rate. Similarly to the FD radio for wireless systems, the SI (downstream to upstream interference at the cable modem) is the main performance bottleneck. Specifically, the SI is mainly due to leakage at the two-way splitter of the cable modem as well as due to the reflections from the modem's taps.

Although SI mitigation follows the same principles with the FD radio (cancellation in the analog domain and then the residual interference is further mitigated at the baseband), wireline communications are characterized by a mainly static SI channel with a larger bandwidth and delay spread. It is obvious that a static SI channel simplifies the echo's estimation and cancellation process; on the other hand, in this case, the FD design should take into account multiple echoes with a large power and delay as well as a strong transmit noise. All in all these are the main technical challenges associated with the implementation of the FD technology in wireline systems. It is worth noting the FD has been already adopted for next-generation cable modems i.e., CableLabs DOCSIS-4.0 standard, while it is an essential part of the MGFAST technology.

Q6: How critical is upper layer design so that gains promised by full-duplex can be reaped? Are there any performance bounds, new theory to be developed? What are the practical issues?

To achieve the full potentials of the FD technology, a cross-layer optimization framework that takes into account sophisticated signal processing and resource allocation techniques is required. The concept of FD radio imposes inevitable additional interference in multi-user networks, making the resource allocation problem more complex compared to its half-duplex (HD) counterpart. Consequently, conventional medium access control (MAC) protocols, such as the carrier-sense multiple access with collision avoidance (CSMA/CA) protocols, cannot be directly applied to FD networks. To reach the potential capacity gains from the FD operation, it becomes necessary to intelligently schedule appropriate downlink and uplink users with corresponding transmission powers/rates so that an aggregate network utility maximization is achieved. Therefore, cross-layer optimization between the physical and MAC layers is necessary and vital in order for the FD technology to be integrated and realized in complex multi-user networks.

Q7: Full-duplex is touted to implement 6G. What are the "anticipated" 6G applications that could benefit from FD operation? Do you think FD will play a complementary role for mmWave and THz communication systems? What path would device manufacturers, service operators would take?

The application of the FD radio in future 6G networks can potentially double the spectrum efficiency and the throughput capacity as compared to the conventional HD systems. Hence, emerging applications with high data rate requirements, such as augmented reality, three-dimensional (3D) gaming and "tactile Internet", will experience significant gains from the FD technology. Furthermore, since the transmission and reception of an FD-enabled transceiver is performed in the same time/frequency resource block, the latency in 6G communication systems can be substantially reduced. Therefore, services and applications that demand virtually zero latency, such as vehicular communications, remote healthcare monitoring, localization etc, will benefit from the employment of the FD radio in 6G communication systems.

The design of FD radio in higher frequency bands, such as millimeter-wave and tera-hertz communications, will be a promising solution. Initially, given that the concept of FD radio enables non-orthogonal transmissions and receptions, the huge available spectrum associated with the higher frequency bands can be utilized more efficiently than before. Furthermore, the high directivity of high frequency signals not only indicates the high antenna gain for throughput improvement, but also enhances the spatial reuse, mitigates the interference in the presence of concurrent transmissions, and assists in passively mitigating the SI in FD implementations.

Q8: Machine learning and artificial intelligence technologies are increasingly used in wireless communications. What could they provide for SI cancellation / FD implementation / FD applications?. How will they complement signal processing and radio implementation in FD transceivers? What are the challenges?

With the unprecedented availability of data, requiring software-controlled and optimized operations, artificial intelligence and machine learning are destined to play a key role in the FD technology. Specifically, by using machine learning tools, the non-linearities imposed at an FD transceiver, such as non-linearities associated with the digital-to-analog/analog-to-digital converters, the IQ imbalance, the phase-noise and the power amplifier distortion, could be efficiently modeled and compensated in order to generate a reliable SI cancellation signal. In addition, by utilizing the potentials of machine learning tools, the multi-user interference can be efficiently alleviated by jointly addressing a wide class of resource allocation problems, such as power control, link scheduling, user's operation mode (e.g. FD, HD), antenna directionality design, etc.

Q9: How lessons learned from self-interference cancellation in-band full-duplex communications can be applied to other scenarios (e.g., digital pre-distortion, adjacent channel leakage)?

Indeed, the fundamental idea of the SI suppression and the associated mitigation techniques can be applied to other communication and engineering problems. Several applications such as audio and acoustic signal processing, control systems, radar systems etc are characterized by structural echo channels and thus can be resolved through "SI-like" cancellation techniques. In addition, problems such as the adjacent channel leakage associated with the non-linear effects of the high-power amplifiers also resemble "SI-like" phenomena. Therefore, such problems could be further compensated by applying advanced SI techniques as well as key methodologies from the FD literature. Overall, the SI and the associated mitigation techniques appear as a general engineering concept with several potential applications.

Q10: In your view what are the key outstanding issues remain to be solved so that FD could become a ubiquitous technology used in wireless and wired systems?

A significant portion of the SI suppression relies on the propagation/analog/digital domain cancellation techniques, which often require additional (and often sophisticated) circuitry. Although this may not be a critical problem for some infrastructures (e.g., base stations), more and more emerging communication devices (e.g., smart-phones, laptops, tablets, sensors etc) have limited computational resources and restricted form factor. Hence, the design of low-power, low-cost, small-form-factor analog and digital circuitry for SI suppression, is of critical importance for both wireless/wireline FD communications. In addition, the FD technology affects all the layers the protocol stack and thus increases the complexity of the whole network. Its implementation requires efficient and robust cross-layer techniques that take into consideration the co-design of scheduling, routing and networking with the physical layer, while keeping the power consumption within acceptable levels.

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Interview with Prof. Özgür Gürbüz

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Q1 Summary of your research, so far what are the important results obtained?

A1 We have been working on full duplex (FD) communication for a while, at different levels and layers. Having observed the potential benefits of FD in the link layer and higher network layers and how much the gains are dependent on FD radio implementation, specifically self-interference (SI) cancellation capability, we have started working on FD radio technology. Here, I would like to provide a review of our works on FD radio design, and I can summarize our works on FD in upper layers, a little later, in a related question.

Unlike most FD radio designs, which employ multiple antennas, or a single antenna with a duplexer/circulator and additional analog cancellation circuitry, at Sabancı University, we have developed a low-complexity single antenna FD radio, by employing only passive (antenna) suppression and digital SI cancellation (via time and frequency domain estimation and reconstruction algorithms) on WARP v3 software defined radio board with Orthogonal Frequency Division Multiplexing (OFDM) based WiFi (IEEE 802.11g) air interface [1]. In [2], we have performed extensive tests with our monostatic antenna FD radio, considering different antenna designs, various positions and orientations of the antennas, and we have demonstrated bi-directional communication between two FD radios via Error Vector Magnitude measurements. We have presented that with our FD radio design, up to 99 dB total SI cancellation can be achieved, promising successful FD communication for low to moderate range applications. In the same work, we have also developed a detailed model for characterizing the behavior of the single antenna FD radio, formulating the power of the residual SI signal as a function of transmit power level, providing an improved and generalized model to be utilized for analysis of FD in upper layers.
Lately, we have been working on improving our monostatic FD radio via additional nonlinear digital cancellation employed at the baseband level only, again without any hardware modification or addition. In our integrated linear and nonlinear digital SI cancellation framework, linear and nonlinear effects are decoupled via two approaches, which we name as nested and residual methods, and nonlinearity is addressed via three alternative solutions, memory polynomial (MP), Support Vector Regression (SVR) and Least Mean Squares (LMS) based solutions [3, 4]. Using our integrated residual approach with MP, our monostatic FD radio with linear only digital cancellation has been improved by 6-7 dB higher total cancellation at low-to-moderate transmit power levels, and 6-7 dB improvement is achieved at high transmit power levels via our integrated nested approach with SVR [4].

We are continuing our efforts on the same setup and with the integrated approach for nonlinear cancellation via machine learning based solutions and we have some preliminary results, promising that with optimized learning, SI can be reduced down to the noise level at higher power levels. As another improvement to our monostatic FD radio, in [5], we have proposed baseband level techniques assisting linear frequency domain SI cancellation, providing not only higher cancellation but allowing our FD radio to work resiliently in multi-path environments. On top of these enhancements, we are also working on alternative solutions for nonlinear cancellation, also considering frequency domain approaches, and we have started extension of our FD radio with Multiple Input Multiple Output (MIMO) features.

Q2 Can you explain the self-interference problem? Summarize worldwide efforts and

progress so far to solve the SI issue (propagation / analog / digital / spatial domain SI cancellation)

A2 In the current half duplex (HD) systems, transmit and receive operations are isolated either by time or frequency division duplexing. FD wireless communication allows simultaneous transmission and reception in the same frequency band, promising twice spectral efficiency and link rate, provided that the SI signal is sufficiently cancelled.

In an FD radio, both a signal of interest (SoI) from a distant transmitter and the SI signal from the co-located transmitter are received. Since the SI signal follows a shorter path in comparison to the SoI, it creates a high level of interference on the SoI at the receiver. To capture the SoI during transmission, i.e., to enable FD communication, the SI signal must be suppressed to the noise level. This is provided via passive and active SI cancellation techniques applied at the receiver.

While passive suppression is achieved at the antenna level, active SI cancellation is performed via analog cancellation at the radio frequency level or digital cancellation at the baseband level. Spatial suppression is another approach to cancel the SI signal by utilizing multiple antennas in MIMO systems. By all means, SI suppression/cancellation aims to replicate the SI signal and then subtract it from the received signal. Antenna and RF level techniques try to generate an analog reference signal with a similar nature to the SI signal, whereas digital techniques aim to estimate the linear and nonlinear effects, which are then used to reconstruct the SI signal at the baseband. Different techniques are combined in FD radio designs, depending on the desired level of total SI cancellation.

Q3 Full-duplex has been proposed for a variety of use cases such as: simultaneous spectrum sensing and communication for cognitive radio applications, fast channel estimation, simultaneous transmission and jamming for physical layer security, uplink/downlink transmission for simultaneous computation and communication etc. What needs to be done so that they could be adopted in practice?

A3 All these are possible immediate applications of FD communication and operation. Another natural use case is random wireless access, where collisions can be detected during transmission and hidden node situations can be reduced due to simultaneous transmissions of two nodes, all leading up to enhanced network throughput. FD can be widely applied for any of these use cases, only if FD is included as a feature in the standards defining the specific air interface of the use case. For practical implementation, the main challenge is in system design, determining the levels (antenna, RF, baseband) of SI cancellation and how to integrate them. Some use cases may require auxiliary receive chain(s) or power amplifiers with increased linear regions to avoid nonlinearity and to assist SI cancellation.

Q4 Despite many years of significant theoretical and experimental work, full-duplex is not considered for 5G, What are the reasons? Will this change? What would be the first FD indoor / outdoor applications that could emerge?

A4 I think one of the reasons for this is timing; before the advance in practical implementations and applications of FD, the first version of 5G standards was already ready. The implementation and integration of SI cancellation stages (antenna, analog/RF, and digital cancellation) on a single chip is challenging, and also especially the analog/RF phase needs high precision design and these challenges could have limited the motivation of device vendors for applying FD in all devices in a cellular network. Furthermore, when FD is employed in the entire system, intra-cell and inter-cell interference issues raised from the increased amount of simultaneous streams need to be addressed, requiring careful planning and scheduling at the system level, as in e.g., [6].

With all these concerns, FD could not be included as one of the fundamental features of

5G, among millimeter wave (mmWave), beamforming, and massive MIMO. However, I think this can change in the later version(s) of 5G. FD can be one of the complementary or optional features to be applied at certain parts of the network, or for some users, or based on their applications. Research is also underway for mmWave FD and massive MIMO FD, so I believe, it is only a question of how and when will FD be included in the standards, not if.

For indoor applications, I think FD is a promising technology for WiFi networks. Recently, FD has been included among the technologies to be studied for the next generation WiFi, IEEE 802.11be, also named as WiFi 7 [7]. Both in-band and multi-band FD communication are to be considered in the discussions planned to start by January 2021. Due to symmetric throughput and low latency, FD WiFi is envisioned for interactive video applications, such as augmented reality (AR), virtual reality (VR), gaming, and teleconferencing. For outdoor, I think FD relaying for fronthaul and backhaul links for cellular networks will be the first application. Surely, FD relaying in WiFi mesh networks (both indoor and outdoor) can be another natural application.

Q5 Could you talk a bit on wired FD standards such as DOCSIS, G.mgfast etc. What are the challenges / what are the differences as compared to wireless? How far standardization has progressed?

A5 Despite the fact that in-band FD communication was originally developed for wireless, the cable industry went ahead and set the first FD standard. In October 2017, CableLabs released Full Duplex DOCSIS (now part of DOCSIS 4.0) standard, providing bidirectional rates of up to 10 Gbps over cable networks [8]. Recently G.mgfast technology has been prepared by ITU-T, bringing bidirectional rates up to 10 Gbps over copper pairs, by introducing FD in addition to the features, such as expansion of frequency spectrum and advanced coding [9].

Achieving FD streaming in DOCSIS 4.0 or G.mfast had challenges of its own ande DOCSIS 4.0 involved similar RF challenges as the wireless case. However, the motivation and success behind standardization of FD in the wired broadband access systems is the strong and urgent need for higher upstream rates for accommodating almost symmetric traffic in emerging interactive video applications (such as teleconferencing, remote learning, AR, VR, etc.) without completely replacing millions of customer equipment. Meanwhile, in almost all residences, behind the broadband ingress point brought by wired access, WiFi is the last hop, so the next crucial step is full-duplexing WiFi. That is why, FD is on the radar screen for next generation WiFi7, where both multi-band FD and in-band FD are to be considered [7].

Q6 How critical is upper layer design so that gains promised by full-duplex can be reaped? Are there any performance bounds, new theory to be developed? What are the practical issues?

A6 As mentioned earlier, in our initial works on FD, we considered FD in upper layers. In [10], considering the multi antenna implementations of FD radios and their residual SI model [11], we performed a link level analysis and compared HD and FD communication for basic communication scenarios, namely, two-way (bi-directional), two-hop and two-way two-hop scenarios, in terms of degrees of freedom (DoF). The main conclusion in that work was, the gains of FD at the link level depends on the considered scenario, and highly on the SI cancellation capability.

Secondly, we considered FD at the medium access control (MAC) layer, and proposed Synchronous Contention Window Full-Duplex (S-CW FD) protocol, as a modification to IEEE 802.11 to enable FD in WiFi networks. It has been shown that, with S-CW FD protocol, the gain of FD in the overall network throughput can be as high as an order of magnitude when there are hidden nodes in the network [12]. S-CW FD protocol has been presented in the meetings of IEEE 802.11 FD Task Group, and due to its performance, low-complexity, and inter-operability with HD 802.11 nodes, S-CW FD was included in the task group's final report [13] as one of the candidate protocols for FD WiFi. Work on FD communication and FD MAC is on the agenda for the next generation WiFi 7, a.k.a IEEE 802.11be [7].

Considering FD at the network layer, in [14], we have proposed a joint power control and routing scheme for multi-hop FD wireless networks, considering a full-interference scenario, where all nodes hear each other, as in indoor wireless (WiFi) mesh networks. Via detailed numerical experiments considering different system parameters, such as, network size, SI cancellation capability and maximum power level per node, it is shown that the proposed FD multi-hop relaying with power control based on the full interference model outperforms not only HD relaying, but also an existing FD relaying solution based on a single-hop interference model: For low power budget systems, HD throughput can be doubled, while for systems with high power budget, proposed FD relaying can double the throughput of FD relaying with power control based on single-hop interference model. When routing is applied jointly with power control, proposed FD routing based on full interference is shown to provide double the throughput of FD routing based on single-hop interference, and to improve HD routing by a factor of five times for moderate SI cancellation levels. Our results have revealed the conditions and potential gains of FD multi-hop routing under full interference, which can be considered as the performance (upper) bound for indoor multi-hop mesh networks.

On the practical side, considering FD implementation at the lowest, physical layer, the main challenge is the training overhead, which is the time required to estimate the linear and/or nonlinear channel. Unless SI signal estimation is done in the presence of the SoI, each node involved in FD communication needs to have an isolated training phase where it transmits alone (in HD mode) and estimates its own SI channel. When packet preamble can be utilized, FD communication results in only an extra preamble duration, which can be quite small as shown in [1]. At the next, MAC layer, the protocol design should consider not only this training phase, but also power control when an access point is involved, as shown in [4] and [15]. For realizing FD in a multi-hop network, it is essential to design a cross layer MAC and routing protocol, so that all channel states can be updated timely and the updated information can be utilized for joint power control and routing calculations and decisions.

Q7 Full-duplex is touted to implement 6G. What are the "anticipated" 6G applications that could benefit from FD operation? Do you think FD will play a complementary role for mmWave and THz communication systems? What path would device manufacturers, service operators would take?

A7 The European Technology Platform, Networld 2020, in the Strategic Research and Innovation Agenda 2021-27 [16], has specified FD as one of the enabling technologies for the next generation radio interface, among mmWave, Terahertz (THz) and optical communication, massive and ultra-massive MIMO, new waveforms and non-orthogonal multiple access (NOMA) techniques. While complementing those upcoming technologies, the applications where I anticipate FD to be realized are fronthauls/backhaul links, mmWave links and networks, and FD power and information transfer.

Research for mmWave FD is underway, however, there are still details to be resolved for making FD work with high number of antennas and beamforming, wide bandwidth in mmWave communications, in addition to antenna and RF design at the mmWave frequencies. The steps for full-duplexing in mmWave frequencies can shed some light for FD for THz communication, which is getting increasing attention for 6G, due to the huge bandwidth offered. However, the design of THz transceivers is still in its infancy. For FD in new waveform designs and NOMA, digital cancellation techniques will need to be adapted. Simultaneous information and power transfer is another emerging application of FD, which can be realized in energy constrained networks, such as IoT applications. All these issues can be addressed when the standards and specifications are prepared by the device manufacturers. I believe, once standardized and deployed, the service operators can highly benefit from the enhanced spectral efficiency and lower latency that FD technology can bring to any air interface.

Q8 Machine learning and artificial intelligence technologies are increasingly used in wireless communications. What could they provide for SI cancellation / FD implementation / FD applications?. How will they complement signal processing and radio implementation in FD transceivers? What are the challenges?

A8 Considering SI cancellation, machine learning (ML) can be applied for nonlinear digital SI cancellation for improved cancellation performance or reduced complexity. For the implementation of FD in multi antenna or MIMO radios, ML based techniques can be applied along with MIMO signal processing algorithms. As an alternative FD implementation, SI channel estimation can be performed in the presence of the SoI, which is another problem where ML techniques can be applied together with signal processing. The main challenge is coming up with low complexity and fast converging ML solutions.

At the network level, ML and artificial intelligence (AI) techniques can be applied in selection of FD users and interference management, considering the network and channel conditions. Also, FD communication can be preferred for certain types of applications; hence classification and identification of applications along with user selection can be performed with ML/AI techniques for enabling FD communications. All such approaches will be well aligned with the vision of 5G and beyond networks. The main challenge for these ML applications is in the collection of network and channel state information, which can be addressed by the cloud/edge/fog computing technologies.

Q9 How lessons learned from self-interference cancellation in-band full-duplex communications can be applied to other scenarios (e.g., digital pre-distortion, adjacent channel leakage)?

A9 One of the main problems in SI cancellation is the nonlinearity in the FD radio, which is mainly caused by the hardware, especially the power amplifiers (PA) at the transmitter and receiver. Results and models obtained via nonlinear estimation for FD communication can be utilized to build digital pre-distortion structures for linearizing the transmit chains of any radio, for FD or HD operation.

Preventing adjacent channel leakage is another possible usage of SI cancellation. With the help of digital SI cancellation, a transmitting radio's interference in an adjacent channel can be estimated and reduced, resulting in lower complexity transmit filters. Similarly, for multi-band FD communication, nonlinear digital SI cancellation techniques can be utilized to cancel the adjacent channel interference, so that instead of costly RF filters, simpler filters can be sufficient for isolating the frequency bands.

Q10 In your view what are the key outstanding issues remain to be solved so that FD could become a ubiquitous technology used in wireless and wired systems?

A10 I think, in the wired systems, FD has already been standardized and ubiquity is only a matter of time. For wireless FD, the key issues are in design complexity, interference management and standardization.

FD radio design involves challenges due to hardware imperfection and non-linearity, non-ideal frequency response of the circuits, phase noise, etc., especially with MIMO and massive MIMO implementations. Due to the increased number of simultaneous transmissions in the wireless network, interference management also needs to be perfectly handled to ensure the gains with FD. Last but certainly not least, as in any technology, for wireless FD to become a ubiquitous technology, not only specifications but also the terms and conditions of when and how to apply FD need to be standardized. WiFi 7 is taking the first step in this, as FD is among the considered technologies for IEEE 802.11be. The main open questions there to be answered are the integration of FD with MIMO/OFDMA based MAC and backward compatibility so as to achieve real deployments of the FD solution in WiFi7 [7].

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Interview with Prof. Chan-Byoung Chae

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Q1: Summary of your research, so far what are the important results obtained?

A1: We first started prototyping real-time full-duplex systems in 2013, debuting the system at IEEE Globecom in 2014. For this system, we implemented the LTE R8 framework on NI’s PXIe platforms and applied our analog and digital cancellation algorithms [1]. In 2015, to further enhance the data rate, in 2015, we also demonstrated a real-time full-duplex MIMO system at IEEE Globecom [2]. In 2016, we designed and demonstrated wideband network full-duplex, in 2017 [3], opportunistic map-based flexible duplex [4], multiuser full-duplex in 2018, and reinforcement learning-based flexible duplex in 2019 all at IEEE Globecom. In addition to these hardware platforms, we also designed a 3D ray tracing-based system level simulator that even included an RF active cancellation part. Over the last nearly nine years, we have tried to verify, in practical scenarios, the feasibility of the full-duplex concept. Recently, we have shown, with an industry partner, that the full-duplex can easily be applied to integrate access and backhaul (IAB) systems [5].

Q2: Can you explain the self-interference problem? Summarize worldwide efforts and progress so far to solve the SI issue (propagation / analog / digital / spatial domain SI cancellation)

A2: Self-interference is a problem that arises when a transmitted signal is itself a source of interference with its own receiver. Considering the gap between high transmit power and noise level, in practical systems self-interference needs to be suppressed by more than 100 dB. To achieve this, researchers have proposed and studied various self-interference cancellation (SIC) approaches. One of the simplest SIC approaches is suppressing self-interference in the propagation domain. This can be done by using directional antennas or polarized antennas, separating transmit and receive antennas, and blocking transmit and receive antennas. Analog SIC can be implemented with circuitry consisting of attenuators, phase shifters, or delays that mimic self-interference and, through destructive interference, cancel it. Self-interference can be modeled and estimated through digital SIC. Therefore, it can be categorized as linear and nonlinear SIC according to what model is adopted. Spatial domain SIC uses multiple antennas for nulling self-interference.

Q3: Full-duplex has been proposed for a variety of use cases such as: simultaneous spectrum sensing and communication for cognitive radio applications, fast channel estimation, simultaneous transmission and jamming for physical layer security, uplink/downlink transmission for simultaneous computation and communication etc. What needs to be done so that they could be adopted in practice?

A3: As mentioned earlier, self-interference is the most important technique for full-duplex. Not only is its cancellation performance (in dB) crucial, but so are its complexity, robustness to various channels, and standard compatibility are. Moreover, as the number of transmitting devices increases, a critical role is played by interference management in the upper layer.

Q4: Despite many years of significant theoretical and experimental work, full-duplex is not considered for 5G, What are the reasons? Will this change? What would be the first FD indoor /outdoor applications that could emerge?

A1: The main reason is that interference management for full-duplex was not good enough for practical applications. Interference here includes self-interference and cross-link interference. Due to increased transmitting nodes, cross-link interference (from other neighbor cells) significantly degrades system throughput. However, SIC techniques have today been improved and developed to be applicable in practical systems (small size, low power consumption, etc.). Also, numerous researchers have studied cross-link interference management techniques for full-duplex. Therefore, for a specific scenario in which interference can be relatively easily managed, we expect full-duplex to be applied. As noted above, IAB would be a good application that could be applied full-duplex [5]. Of course, one should consider ROI (return on investment) as well. For RF active cancellation, what deeply needed are low-complexity, low-power IC chips.

Q5: Could you talk a bit on wired FD standards such as DOCSIS, G.mgfast etc. What are the challenges/what are the differences as compared to wireless? How far standardization has progressed?

A5: Personally, I have focused on wireless; I do not know a great deal about wired FD standards. I suppose the cancellation parts should be different due to the differences in channels, especially, the self-interference channel.

Q6: How critical is upper layer design so that gains promised by full-duplex can be reaped? Are there any performance bounds, new theory to be developed? What are the practical issues?

A6: If we care only about point-to-point communication as in military cases, we do not need to worry about the upper layer design. However, when we consider multiuser scenarios such as WiFi, LTE, 5G, the smart user scheduling is critical to achieve theoretical performance gains [6].

Q7: Full-duplex is touted to implement 6G. What are the “anticipated” 6G applications that could benefit from FD operation? Do you think FD will play a complementary role for mmWave and THz communication systems? What path would device manufacturers, service operators would take?

A7: Full-duplex can, by definition, double spectral efficiency. So it helps the sub-6 GHz band, which suffers from a lack of spectral resources. MmWave and THz communication systems have short ranges (or cell boundaries), which give rise to small (micro/femto) cells. If we employ full-duplex sub-6 GHz, we can cover a wide area. Also, in mmWave and THz band, we can apply full-duplex techniques for relay or wireless backhaul to support a wide area.

Q8: Machine learning and artificial intelligence technologies are increasingly used in wireless communications. What could they provide for SI cancellation / FD implementation / FD applications?. How will they complement signal processing and radio implementation in FD transceivers? What are the challenges?

A8: One possible problem we could tackle is the non-linearity issue. This problem is caused by digital-to-analog converter (DAC) and ADC non-linearities, IQ imbalance, phase-noise, and power amplifier non-linearities. The conventional polynomial models have a high implementation complexity as the number of estimated parameters groups rapidly with the maximum considered non-linearity order. To reduce the computational complexity, we can, as an alternative, use neural networks. Still, it poses delay issues but is worth studying further to come up with practical modules. Another problem to making this approach feasible is offline learning.

Q9: How lessons learned from self-interference cancellation in-band full-duplex communications can be applied to other scenarios (e.g., digital pre-distortion, adjacent channel leakage)?

A9: This is a good question. A couple of years ago, I bought an AI speaker. When it would play music, the AI speaker was unable to recognize my voice commands due to the volume of its own playing. I thus applied modified SI cancellation and successfully improved its sensitivity to my voice. This is one example of my using a lesson learned from FD radios.

Q10: In your view what are the key outstanding issues remain to be solved so that FD could become a ubiquitous technology used in wireless and wired systems?

A10: I think the key issue is how simple of a design can we use to implement SIC. Current full-duplex systems need a very powerful circuit and complex digital processing. These constitute a large obstacle for full-duplex being applied to various scenarios (or systems) in wireless and wired systems. For example, current SIC systems can be implemented in gNB in cellular systems that can provide power and computation, but it cannot be applied in mobile devices.

Joint work with Dr. Minkeun Chung, Mr. Min Soo Sim, and Mr. Soomin Kim

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Feature Topic: Integrated Space-Aerial-Terrestrial Communications
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As space and aerial platforms can offer much more effective services than traditional terrestrial communication infrastructures, like larger coverage area and better signal propagation scenarios, numerous adventurous efforts have been made to seek potential implementation schemes to explore their advantages for the future data services.
On one hand, for the space performs, recently, deploying smaller and less expensive satellites as become the main trend of the space industry, which profits from the maturation of modern design, possessing and manufacturing technologies for miniaturizing hardware components. Hence, the commercialization of low earth orbit (LEO) megaconstellation systems is motivated by increased transmission pressure, flexible network access, and universal connectivity, and there exist several LEO mega-constellation systems plans, e.g., SpaceX, OneWeb, Telesat, Amazon's Project Kuiper, etc.

On the other hand, the idea of "connectivity from the sky" has attracted many attentions from both academia and industry. Still now, there are several types of aerial performs designed and proposed to play as aerial base stations or relays to provide data links for terrestrial terminals, like high altitude plat-form (HAP), low altitude plat-forms (LAP), drones, aircrafts, and airships. By deploying and combining aerial platforms to complement the terrestrial communication infrastructure, the aerial access network will come true and be recognized as a potential solution for the next generation of future wireless communication systems.

However, though considerable merits can be reaped by integrated space-aerial-terrestrial communication (ISATC) systems via integrating space and aerial platforms with terrestrial communication infrastructures, due to the inherent characteristics of ISATC systems, e.g., open channel, heterogeneous interconnection, diversified transmission modes and highly dynamic topologies, there exist numerous open issues and technical challenges in the preliminary phase of ISATC systems, such as holistic system optimization, energy efficiency-oriented traffic integration, and intelligent traffic offloading, information transmission security and user privacy protection, etc.

In this feature topic of this TCCN newsletter edition, we will devote to ISATC systems. Specifically, in this edition we bring together inputs from three active experts in this field, while focusing on the system-level problems: Prof. Pei Xiao from the University of Surrey, Prof. Mohamed-Slim Alouini from King Abdullah University of Science and Technology, and Prof. Jianping An from Beijing Institute of Technology. All of them answer a group of questions in the interview for this feature topic.

Gaofeng Pan is currently a professor with The School of Cyberspace Security, Beijing Institute of Technology, China. His research interest spans special topics in communications theory, signal processing, and protocol design. He received the Exemplary Reviewer Award 2017 and 2019 given by the IEEE TRANSACTIONS ON COMMUNICATIONS.

Interview with Prof. Pei Xiao

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Q1: Nowadays, we have witnessed increasing demands on network coverage/connections ranging from the local scale to the inter-continent scale. Integrated space-aerial-terrestrial communications have been regarded as a promising solution to satisfy such requirements. In your opinion, what is the integrated space-aerial-terrestrial communication system? Could you give some appropriate descriptions to define it?

A1: In my view, the benefits of an integrated network go far beyond coverage extension. A tightly integrated space-aerial-terrestrial communication system should be able to deliver all the use cases and applications for 5G and beyond with extremely diverse and sometimes conflicting technical requirements. The enabling technology is network slicing, which offers an effective way to meet the requirements of all use cases and enables individual design, deployment, customization, and optimization of different network slices on a common infrastructure. Each network slice can be viewed as a virtual network to provide a service with specific requirements. This mechanism can only be fulfilled with a truly integrated network across space-aerial-terrestrial segments with a harmonized air interface as well as a unified pool of communication, computing and caching resources.

Q2: What do you think are the most important challenges faced by developing integrated space-aerial-terrestrial communication systems?

A2: Historically, those systems have been designed and evolved separately. Each has their own requirements and criteria which are sometimes diverging. The most important challenges faced by developing integrated communication systems include i) how to design the integrated network with versatile capabilities that can be dynamically implemented according to varying situations and can cater for the requirements of specific applications; ii) how to design a network that can utilize various communications links provided by air, space, terrestrial segments, and how to unify them under one umbrella. Those challenges can only be tackled under the framework of a truly integrated network mentioned above.

Q3: Apparently, integrated space-aerial-terrestrial communication systems are a kind of heterogeneous network. Could you list some issues on this aspect that should be carefully treated during the development of integrated space-aerial-terrestrial communication systems?

A3: Those issues include (but are not limited to)

- The spectrum allocation among space/aerial/terrestrial and among LEO/MEO/GEO;
- Interference management (e.g., interference can be caused by overlapping footprints)
- Interface design between space-aerial-terrestrial and between the user-plane and control plane;
- Resource sharing between space-aerial-terrestrial segments;
- Dynamic QoS management;
- Robust and seamless handover between different segments of the integrated network (e.g., Sat-Sat, Sat -Terrestrial, etc.);
- Dynamic optimization of network architecture structure utilizing SDN/NFV technologies;
- Integrated network security, e.g., distributed security key management for LEO systems with dynamic topology;
- Application of AI/ML to the integrated system, e.g., for interference mitigation, network management, optimization of resource allocation, etc.

Q4: It is well-known that satellite communications have been developed for decades from

the last century, which is also a key part of integrated space-aerial-terrestrial communication systems. Then, would you like to introduce the main differences in the roles that satellite communications play in these two different stages?

A4: In the past, the development and standardization of satellite systems have been separated from the terrestrial systems. Also they serve different purposes and have different applications. Now they are converging to form an integrated network in which satellite communications have become an indispensable component.

Q5: Now, there are some aerial platforms under development or being studied for incoming wireless communication systems, like UAV/HAP communication systems. What should we do to merge them into integrated space-aerial-terrestrial communication systems?

A5: We need to look at the complementary roles played by UAV/HAP. While satellites are capable of delivering Satellite-eMBB, Satellite-IoT services, HAP and UAVs can play a critical role in providing network service recovery in a disaster region, enhancing public safety networks, or handling other emergency situations when high reliability and low latency (URLLC) is required. Compared to terrestrial communication systems, on-demand communication systems with low-altitude and highly mobile UAVs are generally more cost-effective and more flexible.

Q6: How do you think about the network architecture of integrated space-aerial-terrestrial communication systems? And what are the major differences between it and one of the traditional terrestrial systems?

A6: In the context of integrated space-aerial-terrestrial communication systems, the double-backbone architecture envisaged in [1] for integrated space-terrestrial systems can be further extended to a triple-backbone architecture. Each of the three segments (including space, aerial and terrestrial) has its backbone and access network. The space backbone network (SBN) is comprised of several GEO satellites and the inter-satellite links (ISLs) connecting them. The space access network (SAN) is comprised of a large number of LEO constellations. The SAN consists of subsystems with each providing a specific service. Those subsystems can communicate with the SBN via ISLs or directly communicate with the terrestrial backbone network (TBN) using satellite-terrestrial links. This connection diversity helps achieve real-time communication between subsystems and facilitates the integration of various satellite resources. Similar arrangements can be made i) in the air segment for the air backbone network (ABN) and air access network (AAN); ii) in the terrestrial segment for the terrestrial backbone network (TBN) and terrestrial access network (TAN).

The triple-backbone architecture (consisting of SBN, ABN and TBN) enables immediate data processing, data storage and real-time information sharing, which significantly reduces the transmission latency.

The integrated system differs from the traditional terrestrial systems in i) multi-layer structure and interconnections among different layers /segments; ii) heterogeneous wireless transmission environments; iii) unique challenges in satellite communications such as large transmission latency, nonlinearities, high Doppler, highly dynamic topology, etc.

Q7: Could you give some expectations on the application of integrated space-aerial-terrestrial communication systems?

A7: The integrated systems will be able to provide seamless, ubiquitous wireless coverage and should be able to deliver end-to-end services for all applications and support all vertical industries envisioned for 5G and beyond.

Q8: Would you mind sharing some suggestions or experiences on studying integrated space-aerial-terrestrial communica -tion systems?

A8: The development of satellite systems used to be lagging behind their terrestrial counterparts (with a few exceptions). This provides us the opportunity to extend the terrestrial technologies to satellite communications, such as MIMO, NOMA, OTFS, network coding, etc. However, the extension won't be straightforward due to some unique challenges of satellite communications mentioned above. Good research topics come from seeking solutions to work around the identified problems and to render those cutting edge technologies viable for the integrated space-aerial-terrestrial communication systems.

I also suggest the researchers to closely follow the most recent development in 3GPP standardization. For example, many open issues and technical challenges for the integrated network have been discussed in [2]. Finding solutions to address those challenges would make our work highly impactful and practically significant.

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Interview with Prof. Mohamed-Slim Alouini

Q1: Integrated space-aerial-terrestrial communica-tion system has attracted plenty of attention from both academic and industrial. How do you think about the relationship between integrated space-aerial-terrestrial communication systems and incoming 6 G wireless communication?

A1: In my view 6G will have a two-fold mission: (i) hyper-connecting the connected in order to enable futuristic applications requiring super-high speed connections such as for example: virtual reality gaming and mainstream holographic telepresence technology democratizing 3D holographic video conferencing, and (ii) connecting the unconnected by addressing one of the "blind-spots" of the previous Gs and start offering decent connectivity to people living in not only remote, rural, and/or hard-to-reach areas but also regions affected by a natural disaster or man-made catastrophe. In this context, integrated space-aerial-terrestrial communication is the way to go in order to achieve the second mission of 6G and offer global connectivity in an economically viable and sustainable fashion.

Q2: What do you think is the main technical challenge of integrated space-aerial-terrestrial communication systems? And are there any effective methods to work out them?

A2: Many of the technologies related to integrated space-aerial-terrestrial communication systems such as LEO mega-constellations or high-altitude platforms (HAPS) are still at the prototype stage or Beta testing stage. So much more research funding is needed to get fully operational and eventually profitable communication networks relying on these technologies.

Q3: Could you give us some descriptions of the roles of LEO, MEO, and GEO satellites in integrated space-aerial-terrestrial communica -tion systems? Especially the potential roles of each kind of satellite.

A3: Satellite communications are needed to back-haul in a cost-effective way remote areas. GEO satellites offer a very wide coverage but suffer from a high latency. On the other hand, LEO satellites have a limited coverage area and are not in a fixed location with respect to the ground but offer low latency back-hauling capabilities which may be critical for certain applications. MEO constellations offer a trade-off between these two aforementioned solutions.

Q4: Integrated space-aerial-terrestrial communication systems consist of various kinds of existing communication systems and techniques. Then, what do you think we should do with these traditional systems to embrace them into the emerging integrated space-aerial-terrestrial communication systems?

A4: Global coverage without relying on the deployment of costly infrastructure on the ground will depend on the deployment of three-dimensional integrated networks that encompass terrestrial, airborne, and satellite communications. As such, it is expected that flying networked platforms, such as Unmanned Aerial Vehicles (UAVs), flying cars, tethered Aerostats/Blimps, and High Altitude Platforms (HAPs) could become ever-present in the 2030's. In this context, novel wireless communication schemes that integrate satellite, airborne, and terrestrial networks and that are aiming to support land, maritime, and flying users and devices. More specifically, these self-organized networks are expected to rely on terrestrial base stations drones, balloons, high-altitude platforms, and non-geostionary satellites that adapt their structure and their resource allocations based on the ground population density and the quality of service requirements by the apps utilized by these population of users.

Q5: Compared to conventional wireless systems, the communication distance in integrated space-aerial-terrestrial communi-cation systems may be longer, like space-terrestrial delivery. Then, how to guarantee the transmission quality in such difficult scenarios while promising the required QoS?

A5: In my view, one of the main motivations behind integrated space-aerial-terrestrial communication systems is to connect standard terrestrial mobile user equipment or IoT devices to the network. This can be done by using terrestrial or airborne relays to guarantee channels with a good signal-to-noise ratio between the terrestrial devices and the relays and these relays can then be back-hauled via satellite links.

Q6: Due to the system complexity of integrated space-aerial-terrestrial communication systems, how to promise information security in such complicated but open scenarios?

A6: To achieve confidential communications, quantum key distribution (QKD) provides unconditional security based on the law of quantum physics and quantum non-cloning theorem. QKD can be implemented with free-space optical (FSO) links which can offer high-speed feeder links between the satellites or the aerial platforms and the terrestrial gateway stations.

Q7: Could you introduce some of the recent advances in integrated space-aerial-terrestrial communication systems?

A7: The last decade has seen great developments in the application of 2D-stochastic geometry tools to analyze the performance of terrestrial cellular and IoT wireless networks. I believe that there is a great potential in this coming decade to capitalize on or to develop new 3D-stochastic geometry tools in order to accurately assess the performance of integrated space-aerial-terrestrial communication networks.

Mohamed-Slim Alouini was born in Tunis, Tunisia. He received the Ph.D. degree in Electrical Engineering from the California Institute of Technology (Caltech), Pasadena, CA, USA, in 1998. He served as a faculty member in the University of Minnesota, Minneapolis, MN, USA, then in the Texas A\&M University at Qatar, Education City, Doha, Qatar before joining King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia as a Professor of Electrical Engineering in 2009. His current research interests include modeling, design, and performance analysis of wireless communication systems.

Interview with Prof. Jianping An

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Q1: How do you define integrated space-aerial-terrestrial communication systems? And what are the key features of them?

A1: Generally, integrated space-aerial-terrestrial communication systems means that aerial systems, satellite systems, and terrestrial communication systems are connected together, and then various kind of heterogeneous devices, systems and networks are linked via Internet to provide much more effective services than traditional communication infrastructures.

There are three key features of integrated space-aerial-terrestrial communication systems arising from its inherent integration: 1) Radio interface design including multiple access, spectrum sharing and utilization, resource allocation, interference management, cooperation transmission, etc.; 2) Network operation and management including mobility management and routing design; 3) Network security.

Q2: What do you think will be the main technical inventions of integrated space-aerial-terrestrial communication systems? And what will be the main difficulties to develop and implement such systems in practice?

A2: First, I want to talk about the main potential difficulties which will be met during the development and implementation of integrated space-aerial-terrestrial communication systems: 1) Challenges of intersystem operations and controls incurred by the heterogeneity of integrated space-aerial-terrestrial communication systems; 2) Difficulties of the commercialization and resistances to commercial operations.

To solve the two aforementioned challenges, we should devote to technical inventions mainly on how to realize optimal intersystem operations and controls among heterogeneous devices, systems and networks for various types of users and traffics.

Q3: Do you believe that integrated space-aerial-terrestrial communication systems will come into our daily life soon? If not, what's your expectation on the timetable of the application of integrated space--aerial-terrestrial communication systems?

A3: Sure, integrated space-aerial-terrestrial communication systems will come into our daily life in the future. However, now it is hard to give an exact timetable of applying integrated space-aerial-terrestrial communication systems. Because there are some unpredictable factors in the way ahead of the maturation, implementation, and commercialization of integrated space-aerial-terrestrial communication systems in our daily life, which are not only from technical areas but also come from some other non-technical areas, e.g., market acceptance and customer satisfactions, etc.

Q4: How do you think about the application prospects of artificial intelligence (AI) technologies in integrated space-aerial-terrestrial communication systems? And what do you think will be the main issues solved or reshaped by AI?

A4: First, AI technologies are a promising tool to tackle with the challenges in wireless communications and networks imposed by the increasing demands, such as capacity, coverage, latency, efficiency flexibility, compatibility, etc. Generally, AI technologies have been widely applied to wireless communication systems for various purposes, such as routing establishment/optimization, and resource allocations. These proposed algorithms are designed with deep learning (DL) technology so as to greatly improve the performance of communication systems based on traditional methods.

As we talked earlier, the unique characteristics of integrated space-aerial-terrestrial communication systems bring the designers, researchers, and engineer huge difficulties in system design, operation, and maintenance. Therefore, compared with conventional optimization methods, AI technologies can serve as a more useful tool to overcome such challenges, not only for dynamic resource allocations but also for interactions across the heterogeneous subsystems in integrated space-aerial-terrestrial communication systems, to achieve expected optimal performance.

Q5: Could you talk about the main security issues faced by integrated space-aerial-terrestrial communication systems? And what can we do to safeguard the information delivery?

A5: Differing from traditional terrestrial wireless communication systems, integrated space-aerial-terrestrial communication systems exhibit some unique characteristics. For example, the communication distances will be much longer and the network architecture will be more complicated. Then, the information delivered in integrated space-aerial-terrestrial communication systems will be much easier to be overheard by eavesdroppers, especially for the information delivery over satellite-to-ground links. Moreover, it is a challenge to safeguard the information delivery by using a unique method in the whole systems. In other words, we should find ways to protect the information transmission by considering the detailed communication scenarios in integrated space-aerial-terrestrial communication systems. Finally, except for traditional encryption technologies in upper layers, some other methods may be able to serve as useful tools to safeguard the information transmissions, like physical layer security and quantum communication technologies.

Q6: In your opinion, what are the main technical aspects included in integrated space-aerial-terrestrial communication systems? As well as the relationship between them.

A6: In my opinion, there are three main technical aspects for integrated space-aerial-terrestrial communication systems: 1) Radio interface technologies which is the bridges among these devices, systems and networks; 2) Network technologies that focus on the dynamic operation and management; 3) Information security technologies referring to the information security issues during the transmission across the whole system.

Radio interfaces are the basic network architecture, network technologies are the principles of how the network runs, and information security is the key promise of users' experience and the basic guarantee of network operations.

Q7: Space and aerial platforms, such as satellites in the space, and HAP/UAV/LAP in the sky, suffer inherent limitations, for example, limited power budgets and computational capacities. Are there any promising ways to design optimal integrated space-aerial-terrestrial communication systems to overcome such drawbacks?

A7: In order to overcome such limitations with these space and aerial platforms, first, some novel power cell technologies should be developed to enlarge the energy budget; second, new power control schemes must be proposed by exploring the network features of integrated space-aerial-terrestrial communication systems, because the traditional power control algorithms focus on terrestrial communication systems and cannot work in integrated space-aerial-terrestrial communication systems; third, we also should find some new energy harvesting methods to realize energy charging for these platforms, as the charging efficiency of the popular solar panels is not as high as expected for integrated space-aerial-terrestrial communication systems; finally, new hardware architectures are required to save power consumption, as well as to realize more power computational capacities.

Q8: Could you introduce some of your works in this area? Like the achievements and plans. Also, could you give the new starters some pieces of advice on the researches on this topic? Like research directions.

A8: No problem. Now our groups mainly focus on the design and implementation of integrated space-aerial-terrestrial communication systems with LEO satellites. In the past, we have successfully developed some resource allocation algorithms for LEO satellites and introduced some access scheme for LEO satellite systems with mega-constellations. In the future, we will study the interactions of various kinds of terminals in integrated space-aerial-terrestrial communication systems, and then try to find out some efficient methods to realize high-efficiency communications in integrated space-aerial-terrestrial communication.

Here, I would like to suggest the new starters to work with the topics related to the unique characteristics of integrated space-aerial-terrestrial communication, which are the main differences from the traditional terrestrial communication systems and also are the key problems on developing efficient integrated space-aerial-terrestrial communications.

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