Ongoing US Signal Processing Research Toward 6G

Xiao-Feng Qi, Narayan Prasad, Guosen Yue, Arkady Molev-Shteiman, Eva Song

Wireless Research Lab, Futurewei Technologies, Bridgewater, NJ

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Introduction

Signal processing has been at the core of communication technology. Today it continues to drive technology innovations for 5G/6G and beyond.

This brief survey highlights recent progress on topics in wireless signal processing (SP) research, mainly in the areas of communication and sensing. It provides historical context and outlook in connection to Futurewei research efforts where applicable.

Rather than duplicating the many survey papers on established trends, we single out *nuggets* of cross-domain analytical formulations and mathematical tools to comment on. As foundational building-block concepts and tools, we believe they hold promise for next-generation communication and sensing breakthroughs.

Surveys like this aim to stimulate open collaboration on early-stage fundamental research efforts, in which Futurewei Wireless Research actively participates, as they often lead to successful commercial rollouts many years down the road, as epitomized by, e.g. massive MIMO study that led to successful 5G deployments a decade later. Understanding the academic directions will help us also coordinate our efforts in terms of directions and where important leadership might lie.

We spotlight the following topics.

- ‘Physical’ Theory of Information
- High-Dimensional Signal Processing
- A New Problem in Sensing
- Online Algorithm
- New Problems in URLLC
- One-Bit Array
- Inexpensive Large Surface?

References are chosen sparingly; insofar as only essential original contributions are concerned.

'Physical' Theory of Information

Lately there are resurgent attempts at deriving information transfer limits of a communication system directly in terms of interaction between electromagnetic (EM) waves and constituent RF circuitry (antenna and analog frontend). Isolated efforts have been ongoing over the years, see e.g. [1][2]. The wireless industry was able to make steady progress without exploiting efforts of this nature. However, the hunt for a post-5G technology capable of delivering yet higher spectral efficiency finally prompts a systematic study of untapped information transfer capabilities native to the Maxwell's equations.

T. Marzetta of NYU is carrying out revealing formulations in this regard; [4] formulated spatially wide-sense stationary channel model satisfying the homogenous wave equation and applied it to tightly spaced arrays. [5] applied multi-port circuit theory to the super-directivity phenomenon of tightly coupled array, with application to wireless communication and power transfer. The efficacy of circuit-based information theory is being demonstrated by B. Hughes's lab at NCSU; Recent works include effect of compact array design and impedance match on receiver estimation error [6], and fundamental information-theoretic limitation imposed by specific array designs [7]. Much remains to be done in this promising field, including application of the circuit-centric approach to optimize practical array and algorithm design.

High-Dimensional Signal Processing

We anticipate signal dimension continue to increase as 6G application scenarios expand beyond communication, to incorporate also sensing and machine learning. For example, MIMO imaging radar signals consist of measurements over antenna and span over multiple timeframes, from which latent parameters such as angles-of-arrival, range, doppler and nature of multiple objects are extracted.

The concept of space-frequency covariance matrix as a high-dimensional (HiDi) channel representation was first introduced by Futurewei in a series of patents (see, e.g. [8][9]) with exemplar applications to MIMO communication (joint beam-delay domain channel estimation) and localization (HiDi RF signature). Extension to other dimensions seems natural (e.g. Doppler).

In a different vein, techniques relying on tensor representation of high-dimensional signals and corresponding processing enters signal processing mainstream since 2016, especially in sensing. D. Sidiropoulos (currently with University of Virginia) and his colleagues have long advocated for applications of tensor-enabled techniques to a wide array of signal processing problems [10]. In fact, they proposed its use for MIMO radar as early as 2010 [11]. However, most tensor related solutions have been hampered by computational complexity exponential in the problem size. Recent progress *in transform-domain* tensor representation, pioneered by X. Wang's group at Columbia University [12], allows proper formal definition of matrix-like computation primitives (such as SVD and QR) and their efficient implementations on commercially available parallel architectures (e.g. GPU [13]). Such work may finally enable wider application of high-dimensional signal processing and machine learning tasks to be carried out on network edge servers.

A New Problem in Sensing

Lately, the rather mature discipline of radar research sees a surge of activities to adapt to autonomous vehicles use, largely propelled by the need to augment (even replace) other sensing modalities to guarantee round-the-clock, all-weather safety. Many known challenges in resolution, dynamic range, multi-radar interference exist (see the many excellent survey papers elsewhere). An overlooked challenge is the so-called *data association* problem. It is a cornerstone problem in multi-target tracking, namely determining which new measurement is associated with which target trajectory across successive radar measurement frames, so that the resulting trajectories track real objects. Classical probabilistic association techniques were pioneered by Y. Bar-Shalom at the University of Connecticut and colleagues in the early 90's (see [14] [15] and the numerous citations thereof, later known as the Connecticut School). They have since found wide-spread applications to this day. In 2018 and 2019, M. Win and M. Meyer of MIT, along with colleagues, enhanced the data association algorithms by employing the message passing algorithm, resulting in complexity-scalable solutions for inexpensive sensing devices [16], and for multiple measurements generated by a single target [17].

However, the classical data association approaches may fall short as the number of objects of various interest (for safety or otherwise) in a vehicular environment far surpasses that typically encountered in classical radar applications, with varying amount of prior parametric information known to the radar receiver. Recently, U. Niesen (Qualcomm, formerly with Bell Labs) and his colleague uncovered a dual problem of mutually enhancing data association and MIMO beamforming via an ambiguity graph approach [18], improving the performance of both. The work provides simple algorithms that offer opportunities for significant enhancement.

Online Algorithm

New applications in communication and sensing involve interactive scenarios where the inputs are revealed to a decision maker over time. The decision maker then needs to make her decisions in real-time *before* seeing all the inputs. The decisions taken must be as competitive as possible when compared to the best ones that would have been taken had all inputs were known in advance. Wireless application scenarios abound, ranging from sensor network experiment design [22], where sensor measurements become available at random times, and the decision is to either ignore it or process it right away (both incur cost); to online MIMO precoder design [23], where a user must be scheduled right away to reduce latency, and once scheduled, his resource cannot be revised in order to maintain a promised QoS. The primary method underpinning solutions to this type of problems is the so-called *online algorithm*. It was considerably enhanced by R. Eghbali's 2017 PhD dissertation at University of Washington [22], which made the method conducive to MIMO network resource optimization and optimal sensor query possible.

The use of an appropriate formulation as well as the choice of right modeling is critical in designing a good online algorithm tailored for the problem at hand [24]. A widely employed model is the so-called ‘worst-case model’ in which the set of inputs as well as the order in which they are presented are chosen by an adversary. This is better suited to situations where the decision maker starts from scratch and has no prior knowledge or experience of the inputs. State-of-art results for this model include those considering non-linear utility functions [21][22]. The latter results offer a potential extension of *submodular* utility maximization results obtained for sensor [27], and our own work on communication networks [28], to online settings. Since the worst-case model can sometimes be too pessimistic, an i.i.d. arrivals model is often employed [23], but its use is questionable in several scenarios. Very recent effort has proposed a model tailored to scenarios in which the decision maker can leverage side information based possibly on prior experience [25]. This model has already allowed an innovative algorithm design for managing real-time virtual machine requests which promise significant revenue improvement for the cloud service provider [26].

Ultra-Reliable Low Latency Communication (URLLC)

It is well known that feedback does not increase channel capacity. However, it improves other transmission performance, e.g., reliability and efficiency. For example, hybrid ARQ via incremental redundancy with the simple ACK/NACK feedback improves packet error rate performance and reduces latency. R. Wessel’s group at UCLA has done extensive research in this direction, including CRC design particularly for reducing undetectable errors [29][30], optimization of the incremental redundancy [31], and reliability output decoding for ACK/NACK without CRC [33]. Early works also include optimizing per-increment rate [32].

However scant attention was paid to a generalized protocol of communications with feedback *beyond ACK/NACK*, largely because capacity/throughput has been singular focus of wireless research. The situation is about to change, as new 5G/6G vertical use cases demand low latency and high reliability in addition to throughput. As an example, earlier work by G. Yue (currently with Futurewei) [34], and Kokalj-Filipovic *et al* [35] provides design for feedback of doped bits for the rateless codes for retransmissions, which significantly reduces the redundancy overhead of rateless transmissions and, consequently, the transmission latency. Such doped decoding feedback techniques need not be limited to rateless transmission. We may look at feedback protocol and channel code design for communication with feedback in a broader light. For URLLC communications, number of retransmissions can be very limited, e.g., 1 or 2, and novel non-ACK/NACK feedback content design similar to [34] [35] points to a new research direction to achieve high decoding reliability.

At a more rudimentary level, an analytical tradeoff between achievable rate, reliability and latency continues to lie at the heart of a fundamental understanding of URLLC systems. Since Y. Polyanskiy (currently with MIT) derived the expression for finite blocklength channel coding rate ten years ago, formally accounting for latency in information theory for the first time [36], much efforts have been dedicated to tradeoff analysis with Gaussian or PSK inputs for single-channel links assuming perfect capacity-achieving channel codes, prominent among them are work by W. Yang [37], and E. MolavianJazi’s 2014 PhD dissertation at The University of Notre Dame [38]. Unfortunately, such analysis is not directly applicable to most practical systems, as they employ QAM constellations, parallel channels (OFDM, MIMO) and practical codes (e.g. 3GPP turbo code). Futurewei research focuses on extending the analytical tools to solve practical challenges in wireless communication. In [39] closed form expressions were derived for parallel AWGN channel with turbo-coded QAM inputs, improving accuracy of link adaptation and block error rate (BLER); in [40] tight achievable BLER for short packet PSK transmission over MIMO block fading channel was derived, and efficacy of linear space-time precoding was demonstrated. Future work may establish formal relationship between MIMO degrees of freedom and system latency/reliability.

One-Bit Array

For quite some time, low resolution ADC/DAC arrays have been an active area of academic study for low-power massive MIMO communication. The concept is recently extended to MIMO radar as well [43]. Much interest has turned to its simplest variant, the *one-bit* fully-digital apertures for communication [41][42] and sensing [44][45], which we believe will benefit 6G wideband massive MIMO communication and sensing systems operating at (sub)THz region, where inexpensive spectra abound, fully digital phased array with a large number of radiation elements promises unprecedented sensing agility and angular acuity for imaging radar, and transceiver power consumption becomes a dominant challenge. Futurewei efforts in this area laid foundation for finite-resolution aperture (including the one-bit version) in theory and practice, including a new analytical model for finite-resolution quantizer array uniquely tailored to communication and sensing applications that simultaneously simplifies transmitter/receiver design (submitted for publication), discovery of novel properties of the quantization noise in a OFDM receiver that facilitates simple wideband MIMO OFDM detector design [46], as well as algorithms for joint resolution adaptation and uplink power control in a wideband system [47].

Inexpensive Large Surface?

In general, the so-called large intelligent surface (a.k.a. reconfigurable intelligent surface, intelligent reflective surface) improves communication efficiency and robustness by manipulating the propagation environment in addition to transmission endpoints. However, propagation environment by nature occupies larger footprint than transmission endpoints. Energy concentration on a receiver, formerly achieved by co-located endpoint apertures (via massive MIMO beamforming) must now be achieved by multiple distributed passive surfaces over a considerably larger surrounding in order to capture sufficient transmitted energy that can then be manipulated by the surfaces. Per-square-foot cost and power must be sufficiently low for the total system cost to be lower than that of a massive MIMO or distributed MIMO systems with similar performance. Therefore, inexpensive low-power surface is critical to its successful commercial deployment, where tailored signal processing techniques are expected to maintain good performance at low hardware cost.

However, system level analyses of performance-cost-power tradeoff between the environment-centric and endpoint-centric approaches are largely lacking. Furthermore, much work is needed to gain fundamental understanding of how the EM transmission characteristics of such surfaces compliment the radio environment, and how such interaction effects system performance. For early attempts see, e.g.[48], [49]. They become difficult if one considers joint surface-endpoints optimization.

Due to lack of fundamental system level understanding especially of the inexpensive surfaces, various US labs carried out over-the-air experiments to directly observe potential of such surfaces for SNR and robustness improvements. In [50] (MIT, 2017), efficacy of a mm Wave mirror for robust VR is demonstrated. In general, high frequency system may greatly benefit from dense deployment of programmable inexpensive surfaces to ensure opportunistic rerouting from blocked paths. The work can be extended to a multi-surface setup to further increase macro diversity. In the low band, lensing effect by large passive surface in a rich scattering environment can be configured to produce higher SNR at desired locations [51] (MIT, 2020), though it is unclear if such enhancement can be made uniform across the floor; A surface made of inexpensive passive elements consisting of an antenna pair connected with a phase shifter 'bypasses' a wall which otherwise blocks the line-of-sight path [52] (Princeton University, 2019).

Summary

We have provided a short synopsis of the outlook and recent progress in wireless signal processing of predominantly US origin. The topics, though somewhat diverse, are chosen for their common analytical rigor and/or inter-disciplinary nature, and their relevance to communication and sensing, the pillar applications driving 6G networks. We hope the report accomplishes its objective of broadening Futurewei's research horizon and engaging the global wireless signal processing research community on directions we deem promising.

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