

Spectrum Management in Near-Field Multi-User Wireless Communications

Yasaman Ghasempour, Arjuna Madanayake, and Josep M. Jornet

ABSTRACT

Employing massive antenna arrays and reconfigurable intelligent surfaces together with recent exploration of higher spectral bands (i.e., mmWave and sub-terahertz frequencies) has unleashed an unprecedented territory where receivers located up to tens of meters from the base station can be within its near-field. In this regime, the typical assumption of far-field channels and planar wavefronts can fail in practical wireless network scenarios. Indeed, in almost all prior work on spectrum management and spatial-spectral reuse, the impact of near-field propagation has been ignored. This article discusses the opportunities and challenges in spectrum management specific to near-field wireless communications. First, this article provides a comprehensive view of the interference models and their differences in near vs far fields. Second, this article illustrates the opportunities presented by exploiting new types of beams that are only available in the near field for multi-user interference and spectrum sharing. Notably, the near-field characteristics are viewed as an opportunity to enhance spatial-spectral efficiency rather than a problem to overcome. Finally, this article provides new trends in digital signal processing for wideband near-field communications and open research challenges.

INTRODUCTION

The development of science and technology in millimeter-wave (mmWave), sub-terahertz (sub-THz), and THz frequencies is one of the accepted paradigms for tackling the spectrum scarcity problem in legacy WiFi and cellular networks. In particular, the large amount of bandwidth available in this spectral region can realize the vision of terabit-per-second (Tb/s) connectivity needed for wireless immersive extended/virtual reality [1] as well as ultra-low-latency backhauling to bring broadband connectivity to remote and rural areas, which is the key to closing the digital divide [2].

However, the path loss in these frequency bands can easily exceed 100 dB over a few meters. On the one hand, the absorption by water vapor molecules leads to extremely high losses at deterministic frequency lines. On the other hand, the small wavelengths of mmWave and THz waves result in very small omnidirectional antennas, leading to high spreading losses. A larger aperture of the transmitter and receiver should be deployed to successfully close a link

at a reasonable range. Large apertures, in the form of fixed directional antennas, lenses, antenna arrays, and reconfigurable intelligent surfaces (RIS), can realize highly directional beams to compensate for the path loss.

The combination of large antenna arrays and higher carrier frequencies yields a paradigm shift. Specifically, in traditional wireless networks at microwave and even low millimeter-wave frequencies (e.g., WiFi, LTE, and 5G), nodes are generally in the far field of the transmitting antennas. In the far-field region, electromagnetic waves can be approximated as spherical waves. For a receiver with a small aperture, the sphere's curvature is not perceived, and planar waves are commonly assumed. These assumptions are the basis of existing channel models widely adopted to study multi-user interference in legacy systems and to derive spectrum-sharing policies.

In contrast, given the smaller wavelength and large antenna arrays in the mmWave, sub-THz, and THz regimes, the near-field range may extend to tens of meters. For example, the near field of a 10 cm planar array at 3 GHz is only a few tens of centimeters, whereas the near-field for the same antenna footprint at 300 GHz extends to a few tens of meters. Unfortunately, early mmWave, sub-THz, and THz channel and interference models based on which early spectrum-sharing techniques are formed are not valid in the near-field region. Moreover, in the near-field, the wavefronts could be neither planar nor spherical but exhibit more complex shapes [3]. Further, mobile users might transition across near- and far-field regions. Finally, a base station or access point may host several near-field and far-field users. All of these motivate the development of new interference models and innovative strategies for spectrum sharing that capitalize on the near-field properties, as shown in Fig. 1.

In this article, we investigate, for the first time, the facts, challenges, and opportunities for interference and spectrum management in the near- and far-fields of mmWave, sub-THz, and THz networks. More specifically, we first illustrate the current literature and open challenges in near- and far-field interference modeling. We then illustrate new spectrum-sharing opportunities enabled by innovative near-field beams. Finally, we discuss the baseband processing needs and challenges for establishing wideband near- and far-field communications.

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INTERFERENCE MODELS IN NEAR VS FAR FIELDS

The differences in signal propagation in the near and far fields motivate the development of new inclusive interference models and spectrum-sharing techniques that can accommodate users in the near- and far-field regions. Specifically, several fundamental questions exist in this regard:

- What is the interference a user experiences in the near field of a far-field-aiming transmitter, and how does it compare to the interference that the same user would experience if it were in the far field?
- How is the near-field multi-user interference when adopting exotic beams designed for near-field communications?
- Finally, what happens to the far-field interference when utilizing such near-field beams? The concepts of far-to-near and near-to-far interference are illustrated in Fig. 2. The answers to these questions will guide new spectrum-sharing strategies for hybrid near-far regimes.

EXISTING LITERATURE ON SUB-THZ CHANNELS

Multi-user interference in sub-THz networks is a well-explored topic. The existing models consider the following three key properties of sub-THz propagation that impact the interference created and experienced by users in the medium.

Molecular Absorption Loss: The molecular absorption loss exponentially increases with distance following the Beer-Lambert law and divides the sub-THz band in multiple transmission windows. Because of the molecular broadening effect, the usable bandwidth within each transmission window exhibits a distance-dependent behavior, which can be leveraged to spatially multiplex users within the same direction using, for example, hierarchical bandwidth modulations [4].

Spreading Losses and Directional Transmission: The small wavelength in the sub-THz regime results in very small antennas. While omnidirectional sub-THz antennas are possible, their small effective area limits the amount of power they can intercept. When making the antennas larger, they intrinsically become directional. Because of the narrow beamwidths, the area in which a transmitting user creates interference is reduced. However, for an *unlucky user* within the transmission beam, the experienced interference is catastrophic.

Blockage by Obstacles: sub-THz signals are effectively reflected and/or absorbed by many materials. As a result, interference diminishes beyond the obstacle. However, if the obstacle reflects signals, interference may increase in its vicinity [5].

In almost all prior interference modeling and spectrum-sharing works [6, 7], users are always considered to be in the far field. As a result, well-established far-field channel models are utilized to estimate the channel of Gaussian-shaped narrow beams, albeit suffering from significant accuracy losses in the near-field region [8]. As a first-order approximation, one can divide the transmitter array into several sub-arrays and estimate the channel by considering the planar-wave model within the sub-arrays and the spherical-wave model among different sub-arrays [9]. Nevertheless, new interference models should be developed to capture the near-field effects and unveil new spectrum-sharing opportunities in this regime.

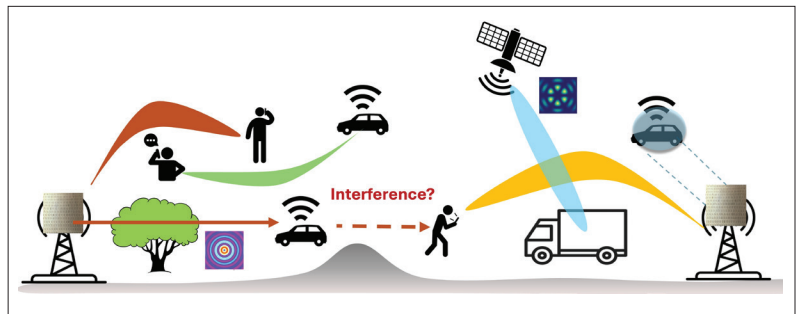


FIGURE 1. New spectrum sharing opportunities from exploiting the unique channel and wavefront properties in the near-field regime. Near-field beams have intriguing properties of spatial focusing (right BS to car), self-healing from obstruction (left BS's signal going through the tree), and curved trajectories (green, orange, and yellow beams), all of which can be leveraged for interference mitigation and programming.

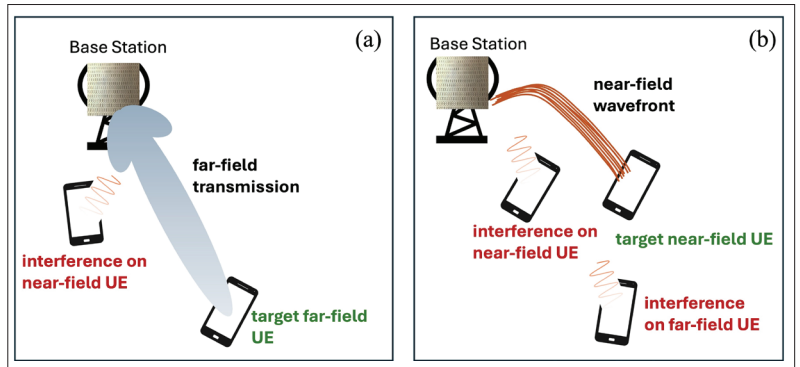


FIGURE 2. Several interference configurations: a) Near-field interference of a far-field aiming transmitter; b) Near- and far-field interference footprint of an example near-field aiming beam with curved trajectory.

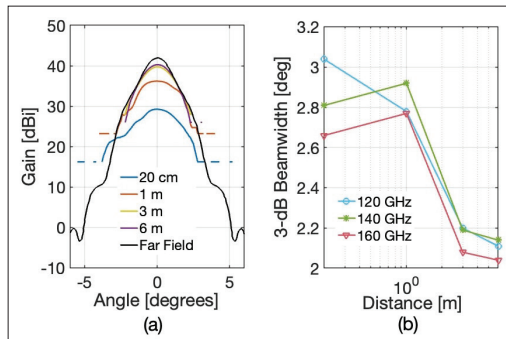


FIGURE 3. Near-field characteristics of radiation pattern: a) Gain at different distances and the expected far-field gain from the antenna specifications at 140 GHz; b) Half Power Beam Width (HPBW) of the radiation pattern observed at each distance for all measured frequencies.

NEAR-FIELD INTERFERENCE OF FAR-FIELD COMMUNICATION LINKS

Even with conventional far-field beamforming, modeling interference in the near-field region of the transmitter is non-trivial, partially because the antenna radiation patterns — which are always measured for the far field — are different in the near field.

Figure 3a illustrates the measured radiation pattern of a 40 dBi antenna operating at 140 GHz at different distances within the near field and includes the far-field radiation pattern in black. We observe that the maximum gain increases and the beamwidth shrinks with the transmission distance. This second trend is easier to see in Fig. 3b. For closer distances, the beam is significantly wider than it is for farther distances [6]. The increased beamwidth in the near field can be especially detrimental in causing interference. These results indicate that even if a

WAVEFRONT SHAPING:

A NEW DESIGN SPACE FOR SPECTRUM MANAGEMENT

The ability to control the spatial profile of the radiated energy has always played an important role in spectrum management. Indeed, well-studied techniques such as space division multiple access were designed based on the principle that the spatial footprint of a directional communication link is limited in space, yielding lower interference unless the two receivers fall into the same *narrow beam*, which is unlikely, if it happens, it causes significant interference [12, 13]. In contrast to most prior work that treats near-field effects as a problem to be mitigated, we view it as a new design space for spectrum management.

EXOTIC NEAR-FIELD WAVEFRONTS

Novel near-field beams have gained attention recently due to their favorable properties, including self-turning (the main lobe follows a curved trajectory in free space), non-diffracting (the waves do not spread out in space up to certain distances), and self-healing (the wave reconstructs its profile after interacting with an obstruction). The theory of such wavefronts has been investigated in the optical community, with a few recent demonstrations in sub-THz wireless networks [11]. However, despite its importance, the role of near-field wavefronts in interference management is non-existent in the literature. Figure 5 demonstrates the three most exciting new-field wavefronts together with far-field Gaussian plane waves.

Focused Beam: The focused beam is a well-known beam that concentrates energy at a single point. This beam can achieve the highest energy concentration, but it requires the perfect knowledge of the receiver location. Furthermore, if the transmitter or receiver moves, the transmitter must adjust correspondingly to maintain performance [10].

Bessel Beam: Bessel beams provide focusing capability over a line instead of a point. This has the advantage of requiring less precise information about the receiver's location relative to the transmitter. Bessel beams also possess self-healing properties, meaning the signal regenerates after a certain distance despite the presence of obstacles, and are non-diffractive, maintaining their shape and intensity over distance [3].

Airy Beam: Finally, Airy beams are also non-diffractive and exhibit a curved trajectory in space. These beams have gained attention in the context of blockage mitigation by optimizing the wave trajectory to curve around obstacles in the medium [11].

INTERFERENCE ENGINEERING VIA WAVEFRONT SHAPING:

CHALLENGES AND OPPORTUNITIES

One interesting and promising research direction is to realize a near-field wavefront adaptation framework that takes into account link performance, channel conditions, and interference objectives. Figure 6 shows an example scenario. As shown, the power captured at the intended RX and the interference imposed on non-target RX both vary significantly with wavefront shaping. Indeed, beam focusing maximizes both received power and interference, whereas an Airy beam significantly reduces interference at the cost of lower power at the target RX. We note the exact amount of delivered power at the target RX is a

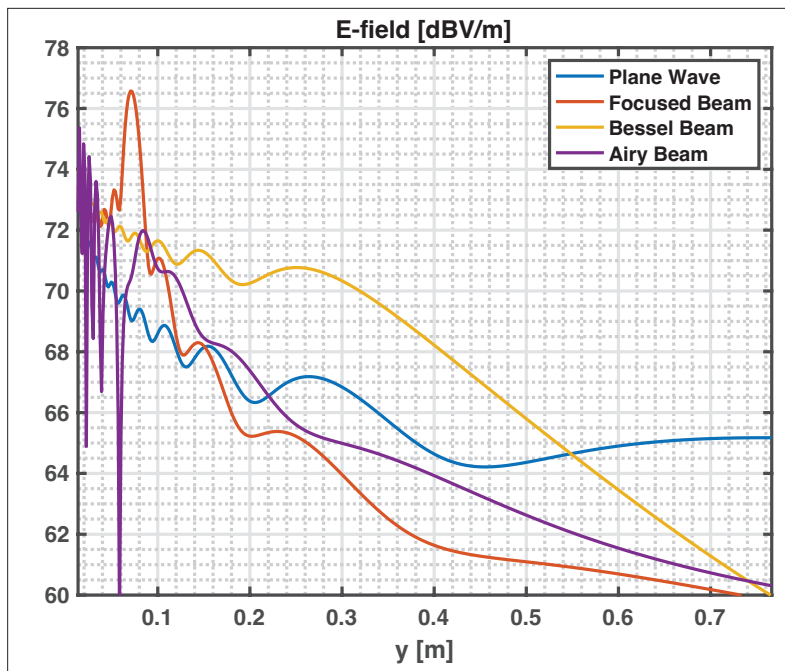


FIGURE 4. Electric field intensity in dBV/m over the propagation distance.

transmitter generates a pencil-thin beam in the far field, the beam can be significantly broader in the near field. Hence, future interference models should take into account the impact of beam broadening in the near field and the antenna radiation patterns.

FAR-FIELD IMPLICATIONS OF NEAR-FIELD COMMUNICATION LINKS

Near-field communications have only recently emerged as a promising new direction for enhanced data rate and wireless security in short-range high-frequency wireless networks. The most well-studied directional beamforming technique in the near-field regime is focused beams [10], where the transmitter focuses its radiated energy on the focal point where the intended receiver is located. More recently, other types of beams have gained attention with new capabilities in the near-field, including non-diffracting Bessel beams [3] and beams with curved trajectories known as Airy beams [11]. We will explain the properties of these exotic near-field wavefronts below. An important question that arises when examining these exotic beams is how they perform outside the region for which they are intended, specifically in the far field.

Figure 4 shows the simulated electric field intensity over the propagation direction for different beams. Compared to a conventional plane wave, a focused beam exhibits a very high-intensity peak at the desired point, whereas a Bessel beam maintains a high intensity over a longer distance. It should be noted that Airy beams follow a curved trajectory, making this result less relevant for them as the electric field is highly dependent on the configured trajectory. Even though these beams decay faster than the plane wave after a certain range, they still propagate to some extent, leaving interference footprints beyond their intended range. An interesting future research direction is to model the far-field interference created by various near-field wavefronts. Such models can provide valuable insights for near-field programming and multi-user interference-free communications.

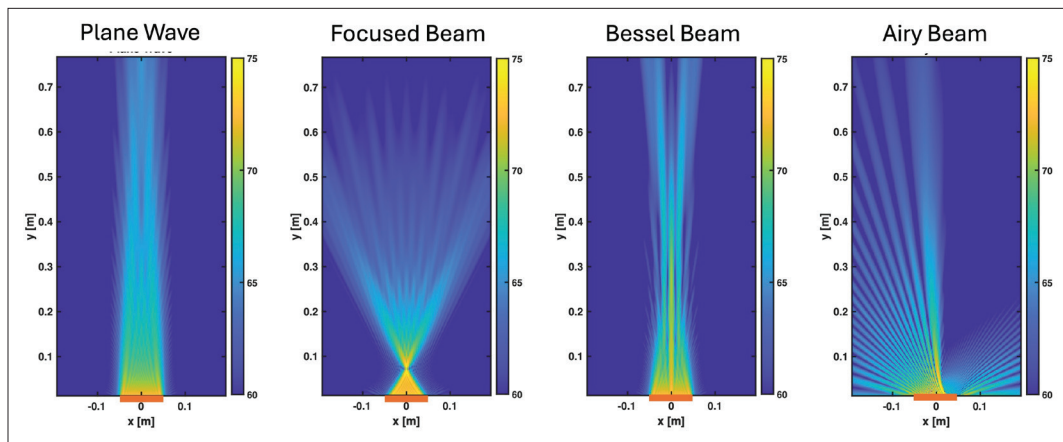


FIGURE 5. Electric field intensity in dBV/m. Left to right: Plane wave, focused beam, Bessel beam, and Airy beam. As shown, the distribution of power in space varies significantly depending on the choice of beam.

function of the Airy beam profile, that is, the exact configured curved trajectory. As expected, the Gaussian beam provides the minimum amount of power at the target RX among all beams. Finally, the Bessel beam creates a non-diffracting linear trajectory rather than focusing the energy into the RX's precise location. Hence, the target RX collects less power under the Bessel beam compared with the Focused beam. The amount of interference depends on the Bessel beam's non-diffraction range vs the secondary user's location.

There are several key barriers against interference engineering via wavefront shaping.

First, the design space is multi-dimensional and massive. Specifically, while existing standards for mmWave and sub-THz bands support exhaustive beam space for directional link establishment (1-D search space to find the best main lobe direction), scaling such schemes to near-field beam configurations is infeasible due to the prohibitively large overhead of covering the entire parameter space. For instance, there are, in principle, an infinite number of curved trajectories that can be formed between the base station and a user.

Second, there is no closed-form model that captures the spatial evolution of waves as they propagate in the near-field regime under an arbitrary transmit electric field profile. The conventional approach is to perform EM simulations that are prohibitively time-consuming and cannot scale to real-time processing and predictions. Alternatively, an open research direction is to develop approximate models and numerical solutions to this problem that are built on the general Rayleigh-Sommerfeld Integral theory. The accuracies of such models, their operating regimes, and performance limits should also be studied.

Third, there are several practical limitations. For instance, how to optimize the wavefront for interference mitigation without Oracle's knowledge of the surrounding environments (e.g., the precise location of blockers/reflectors)? Furthermore, practical antenna arrays have limited aperture sizes and phase/amplitude resolution. These hardware imperfections may introduce grating lobes and aliasing effects, impacting interference experienced by other users.

Finally, large-scale antenna arrays or low-cost intelligence surfaces should be designed and developed at mmWave and sub-THz frequencies,

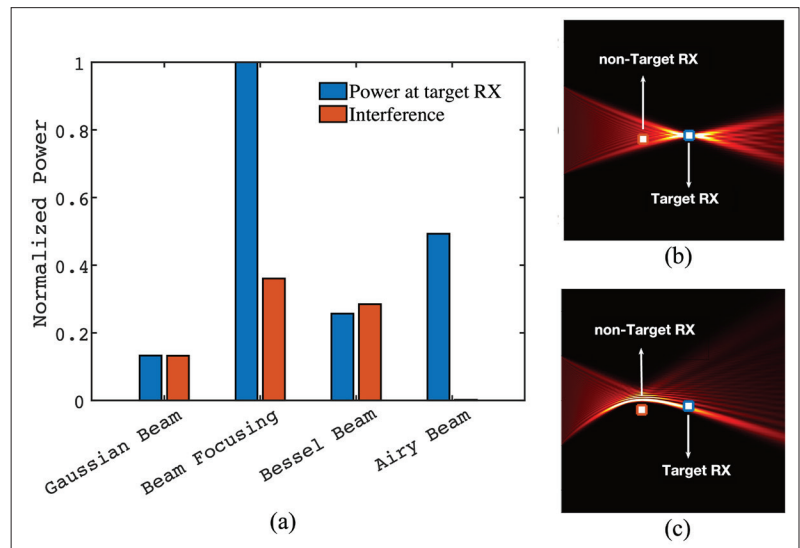


FIGURE 6. a) Power and interference analysis for different beam types in an example two-user scenario; b) Focused beam propagation profile; c) Airy beam propagation profile.

allowing for fast phase and amplitude modification needed for real-time wavefront adaptation in mobile wireless networks.

BASEBAND PROCESSING CHALLENGES IN FUTURE MMWAVE/SUB-THZ RADIOS

The mmWave/sub-THz bands are sought after because of the abundant spectrum and relatively large chunks of continuous bandwidth. For example, it is quite common for sub-THz frequencies beyond 100 GHz to have up to 20 GHz "chunks" of spectrum available for establishing wideband communication links. Hence, spectrum management techniques in the near and far field should consider the wideband nature of these transmissions.

Wideband sub-THz communication links, when observed at their basebands, typically have 10+ GHz of bandwidth at the baseband. To put this into perspective, the baseband signals of the sub-THz channels are larger than the entire sub-6 GHz legacy frequency range plus a part of the frequency range of three (FR3) bands combined. A question arises how we may actually benefit from such humongous bandwidths at baseband when the vanilla software-defined radio (SDR) available

The obvious way to address the massive bandwidth requirements for sub-THz SDR is to use a programmable logic platform that supports such bandwidths.

for designers certainly does not possess the capabilities for processing such massive bandwidths. The problem is two-fold: 1) the SDRs do not have mixed-signal electronics, such as data converters, that support 10+ GHz of bandwidth at the baseband, and 2) these SDRs do not allow the real-time computational throughputs necessary for processing such large bandwidths in real-time.

NEED FOR NEW FAST DSP ALGORITHMS

In wireless communication systems, as we migrate to higher frequencies, the size of the antenna decreases while the complexity of the digital processor (size, area, and power — aka SWaP) seems to grow larger as more bandwidth is available in the higher spectral regime. For example, an SDR operating in the UHF bands may require an antenna about 1 meter in size, which can be implemented in a low-cost SDR chip. On the other hand, a THz radio may have an antenna that is about a mm or two in size, but the SDR may consist of several FPGAs operating in tandem to process the 60+ GHz of baseband bandwidth that is associated with sub-THz bands. This is because the computation complexity of the SDR algorithms increases linearly with the baseband bandwidth. For example, an OFDM core with $N = 1000$ point-FFT that updates 10,000 times a second for a 10 MHz baseband must operate at 10M FFT frames a second for a 10 GHz baseband.

Therefore, the smaller the antennas, the larger the digital backend! In extreme cases, a nano-antenna SDR operating at multi-THz bands may have so much baseband bandwidth that it requires a cabinet full of digital processor chips to process the signals in real-time, which is bad news for THz wideband radios. Therefore, there is a need to not only improve the bandwidths of emerging radios but also to develop new low-complexity fast algorithms that achieve the required level of real-time signal processing for modulation, demodulation, filtering, and coding with sustained throughput at massive baseband bandwidths, without requiring an impractical computing requirement for number crunching in the digital backend. New technologies such as Intel Altera Agilex-9 Direct-RF chiplets combined with low arithmetic complexity algorithms and computer architecture pave the way for true THz radios of the future.

One example of the recent innovations in low-SWaP fast algorithms is the approximate DFT with $\mathcal{O}(N)$ arithmetic (time) complexity [14]. The discrete Fourier transform (DFT) — which requires $\mathcal{O}(N^2)$ operations in its brute force form — is a crucial physics-based transform that maps the time/space domain to its corresponding frequency space. A DFT is commonly implemented using fast Fourier transforms (FFTs) which are a class of fast algorithms that realize the DFT operation at a significantly reduced complexity level of $\mathcal{O}(N \log N)$. The concept of the FFT was imagined by Gauss (unpublished) and realized in modern times as a fast algorithm of high utility by Cooley and Tukey (Princeton and IBM) about 50 years ago. FFTs are considered the most important fast algorithm of modern times, and they play a crucial role in wireless systems, including being the workhorse of cross-correlation, orthogonal frequency division multiplexing (OFDM), spectrum sensing, filterbanks, and spacetime coding.

For real-time sub-THz wireless applications, even FFTs demand a prohibitively high level of computation. To address this issue, an approximated-DFT was created, which has an FFT-like fast algorithm (sparse factorization) that reduces the arithmetic complexity down to a measly $\mathcal{O}(N)$ [14]. This additional reduction by a factor of $\log N$ over the FFTs results in massive savings in computations, particularly complex multiplications, the associated power consumption, and overall system complexity for wireless applications.

However, significant work remains to replace FFT in conventional wireless systems as the $\mathcal{O}(N)$ approximated DFT introduces deviations from filterbank responses, non-orthogonality at critical frequencies, and other trade-offs that require careful engineering. Indeed, the act of approximately computing the DFT to gain a smaller chip area and lower power will result in a loss, albeit small, in performance. For example, it may lead to lower spectral efficiency to gain power efficiency and/or a reduction in bit error rate (BER) to facilitate a cheaper, smaller chip area [15].

ADDRESSING THE WIDEBAND SDR REQUIREMENTS

The obvious way to address the massive bandwidth requirements for sub-THz SDR is to use a programmable logic platform that supports such bandwidths. To our knowledge, there exist only two suitable programmable hardware technologies that facilitate sub-THz wideband SDR in modern times: Xilinx RF SoC and Intel Altera Agilex Direct-RF chiplets. The Xilinx RF SoC platform is a mature technology arising from the AFRL/DARPA Arrays at Commercial Timescales (ACT) program and has been well explored by both academia and industry. Today, the RF-SoCs allow ADC sampling up to 5 GS/s and DAC sampling up to 10 GS/s, basically limiting the channel bandwidths to about 2.5 GHz. The newer Intel Altera Agilex Direct-RF chiplets allow 64 GS/s in both ADC/DAC and instantaneous bandwidths up to 32 GHz.

The Intel Altera Agilex Direct-RF chiplets operate over a 128-phase multirate signal processing framework. One may use multiple bandwidth channels on a multi-channel platform such as Xilinx RF-SoCs with additional analog domain signal processing circuits to spectrally divide a wideband signal into a set of equal-sized, smaller bandwidth analog channels. For example, eight parallel channels, each with a bandwidth of 2.5 GHz wide, provide a 20 GHz baseband, which will be processed as eight parallel FDM channels using an 8-channel RF-SoC.

ANALOG SPATIAL SIGNAL PROCESSORS

At multi-GHz baseband bandwidths, the computational load on the SDR can be so high that the cost and power consumption of such a DSP-based signal processor can be quite prohibitive in a practical sense. One approach to reducing the SDR complexity is to move some of the signal processing load to the passive analog domain by using dielectric lenses, Rotman lenses, and Butler matrices to realize some of the signal processing operations for both spatial and temporal domains using continuous time analog circuits. Optical approaches, including photonic integrated circuit realizations of analog DFTs, can help reduce the load on SDR backends. Following far-field beamforming work such as beamspace-MIMO using dielectric lenses, it may be possible to

realize similar near-field approaches that use new geometries in lenses or metasurfaces to reduce the compute load on the SDR.

CONCLUSION

This article introduces the first overview of innovative spectrum-sharing opportunities in near-field wireless communication in high-frequency regimes (mmWave to sub-THz bands). The article presents the recent literature, unaddressed challenges, and open research questions in this domain. Specifically, we illustrate the differences in interference models for near- vs far-field channels. We introduce wavefront shaping as a new design space for interference engineering and multi-user spectrum management, thanks to the unique characteristics of near-field exotic wavefronts and near-field channel properties. Finally, we investigate the need and recent developments in fast DSP-like algorithms that allow for efficient wideband signal processing and spectrum sensing in near- and far-field communications.

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BIOGRAPHIES

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