NEXT G ALLIANCE
An ATIS Initiative

Next G Alliance Report:
6G Radio Technology
Part I: Basic Radio Technologies

FOREWORD

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INTRODUCTION

Technology has been fueling the global economy's exponential growth over the past few centuries. 6G technology is expected to not only usher in the next wave of digital economic growth, but also drive far-reaching societal shifts in sustainability, digital equality, trust, and quality of life.

The evolution in basic radio technologies is the most fundamental aspect of the next-generation cellular systems having a direct impact on canonical system Key Performance Indicators (KPIs). Part I of this white paper focuses on the fundamental 6G designs at the air interface level.

Enhanced/Ultra-Mobile Broadband (eMBB/uMBB) services are expected to continue to drive toward substantially higher throughput (+100Gpbs) riding on the 6G wireless technology evolution. Examples include advancement in 6G building blocks such as waveform, Multiple Access (MA), coding, and modulation designs).

6G is expected to expand into important new spectrum spanning lower and upper centimeter wave bands and sub-THz/THz bands. 6G needs a large amount of bandwidth to support extremely high instantaneous and peak data rates, as well as high-resolution sensing requirements. To achieve high spectrum utilization, efficient sharing mechanisms between multiple mobile network operators (MNOs) will be necessary. Innovative coexistence techniques could be considered between 6G systems and incumbents, with an eye on protecting passive services. Efficient spectrum sharing can help mitigate interference among overlaid deployments to enable spectrum re-use among licensees. As the radio coexistence environment becomes increasingly complicated from both a device and network perspective, 6G spectrum sharing native design is anticipated to accommodate wide variety of use cases.

A big part of the New Radio (NR) technology, particularly Multiple-Input and Multiple-Output (MIMO) technologies, will be geared toward efficient utilization of the spectrum in new 6G bands and existing 5G bands. Design evolution/enhancement for existing bands, such as a new air interface design for mmWave and/or sub-7 GHz, are also expected in 6G via technologies like spectrum sharing, massive spectrum aggregation, etc.

Various technological advancements in MIMO include Reconfigurable Intelligent Surfaces (RIS), Orbital Angular Momentum (OAM), advanced massive MIMO, and distributed MIMO, in addition to the fundamental physical layer (PHY) building blocks such as waveform, coding, modulation, and multiple-access scheme. All of these will further improve the end user experience in 6G across new bands and existing bands.

Effective utilization of spectrum across multiple bands and frequency ranges with efficient implementation will be essential in achieving high throughput over limited bandwidth resources. Moreover, spectrum efficiency will no longer be the only driving metric in 6G Radio Access Network (RAN) design. Spectrum efficiency will remain important for traditional use cases such as eMBB and media/entertainment use cases. But other use cases will prioritize goals such as spectrum utility, time-sensitive applications, energy-efficient devices, and Extended/Mixed Reality (XR/MR) applications relying on sensor and media fusion. All these different objectives will be provided by a common network supporting different air interface modes or even RATs often capable of using common spectrum bands. Energy-efficient device and network design will become an important topic in 6G radio design and contribute to achieving end-to-end power efficiency in 6G wireless systems from network to devices.

Radio waves in high-frequency bands can be used not only for communication but also for Radio Frequency (RF) sensing purposes for situational awareness from which new use cases such as autonomous driving and XR may benefit. Advanced duplexing technology will play a critical role in both communication and radar sensing for 6G, especially over mid to higher frequencies. With integrated support of Joint Communication and Sensing (JCAS) in cellular systems, new business opportunities could bloom in the 6G era.

While many of these technologies are starting to be discussed in 5G, they will likely not reach their full potential until 6G. Others represent fundamental departures from the concepts and architectures of 5G. Discussions of 6G are just starting, and we expect more new technologies to surface.

2 EXECUTIVE SUMMARY

The rest of this paper is organized as follows. In Section 3.1, new developments in radio technology fundamental building blocks are surveyed. Prospective 6G new designs on new waveform, modulation, coding, and multiple access schemes are discussed for potential spectrum efficiency, and energy efficiency gain over those from previous cellular generations. Section 3.2 covers new 6G spectrum and spectrum sharing mechanisms. In Section 3.3, various advanced MIMO designs (for different frequency bands) are presented, including low FR1 band MIMO enhancements; advanced massive MIMO for higher midband (cmWave frequency range, e.g., upper 6GHz, FR3); massive distributed MIMO for high-capacity seamless cellular experience; and RIS as a new MIMO and network topology technology. Sections 3.4 and 3.5 cover higher frequency air interface designs targeting mmWave and subTHz, respectively, from a radio communication perspective. Section 3.6 explores new service perspectives such as radar sensing, JCAS, and the associated physical layer design. Section 3.7 discusses design considerations and challenges of advanced duplexing technologies for 6G. Section 3.8 introduces holographic beamforming and orbital angular momentum technologies.

3 BASIC RADIO TECHNOLOGIES

3.1

Waveform, Coding, Modulation, and Multiple Access Schemes

Waveform, coding, modulation, and multiple access are fundamental building blocks of wireless cellular systems in every generation. As we evolve towards 6G, these blocks continue to play key roles in advancing technologies and creating new business opportunities. Specifically, to realize the 6G vision, the design comprising waveform, numerology, coding, modulation, and multiple access needs to support enhancements corresponding to KPIs for Spectral Efficiency (SE), power efficiency, and cost efficiency, coverage, reliability, latency, and high-velocity performance. It is also expected to bring performance improvements to existing use cases like Downlink(DL)/Uplink(UL)/Sidelink(SL), Terrestrial Networks (TN)/Non-Terrestrial Networks (NTN), high-throughput operations, and Machine-Type Communications (MTC), and to support new use cases and technologies such as joint communication, positioning, and sensing, PHY security, advanced MIMO, and low-resolution data conversion technologies. To achieve these goals, the four blocks are envisioned to form a unified and highly integrated design, possibly with the help of advanced design tools such as Artificial Intelligence (AI)/Machine Learning (ML), and work jointly to offer flexible and optimized operations for all 6G usage scenarios.

With ever increasing demand for higher data rates and throughputs, spectral efficiency enhancement is important for 6G system design. Scaling up the modulation order and reducing signal (including reference signal) overheads are methods to increase the achievable peak rate. However, limitations such as SNR, channel delay profile, and spectral emission mask requirements may affect their effectiveness in certain usage scenarios. Modulation schemes including non-Quadrature Amplitude Modulation (QAM) constellation designs and constellation shaping could also be used to enhance spectral efficiency. To fully exploit the potential of these techniques, more complex receiver architectures may be required. Index modulation is another modulation scheme that increases spectral efficiency by carrying additional information using subcarrier indexes in a multicarrier waveform or antenna indexes in a MIMO system. When a multiuser system is considered, optimized multiple access schemes such as Multi-User (MU)-MIMO and Non-Orthogonal Multiple Access (NOMA) could also improve overall spectral efficiency.

Power efficiency enhancement is necessary to establish 6G sustainability and critical for ensuring proper operations of many potential 6G usage scenarios. It extends device battery life and reduces overall energy consumption of base stations. It also plays a critical role in meeting link budget requirements for sub-THz communications and NTN. In fact, while enhancing power efficiency, both cell coverage and cost efficiency enhancements could be achieved concurrently. At the transmitter side, the overall power efficiency is largely limited by the Power Amplifier (PA) power efficiency. Signal designs (e.g., low Peak-to-Average Power Ratio (PAPR) waveforms) that enable efficient PA operation are therefore a key component in 6G power efficiency enhancement. At the receiver side, power-efficient signal designs with lower complexity of digital and analog components will play roles in certain 6G use cases such as MTC and sensing networks.

Reliability and latency improvements are requirements for critical use cases such as Critical Machine-Type Communication (C-MTC) and Vehicle-to-Everything (V2X). For improved latency, both waveforms and multiple access schemes should support flexible, short-duration resource allocations for users, while the channel code should provide options to operate reliably with relatively short codeword length. The trade-offs between latency and reliability should be carefully studied.

For communication links operating in high velocity environments (e.g., non-geosynchronous NTN or in a high-speed train), tracking dynamic changes of Doppler frequency shifts is a challenge. Waveform design that is insensitive to Doppler shifts has been proposed. Such design operates in the Delay-Doppler (DD) domain and transforms the highly dynamic channel into a form that exhibits slower variability, regardless of the velocity or Doppler frequency. This allows reliable demodulation and better channel estimation under highly dynamic channel conditions. Doppler pre-compensation is another technology designed to offset the Doppler frequency shifts. It could be applied to various waveforms and can be quite useful for NTN DL transmission. Global Navigation Satellite System (GNSS) dependency is also a major issue for NTN UL transmission. Designing a GNSS-independent UL signal that is robust against timing and frequency errors is of critical importance for 6G NTN use cases.

JCAS is an important new use case for 6G. Information theoretic arguments suggest that communication and sensing could serve independent purposes without compromising each other's performance. How to design a proper signal (including coding, modulation, and waveform) that enables both communication and sensing is a major challenge for 6G. Design considerations may include full-duplex operation, reference signal overheads, etc.

AI/ML have emerged as new tools for wireless communication physical layer design. One key question is whether such tools can be leveraged to craft fundamental building blocks for 6G systems.

To support various 6G scenarios and use cases, it has become apparent that it is unlikely that a single signal design (including waveform, modulation, coding and multiple access schemes) could fulfil all the requirements simultaneously. In this case, a unified yet flexible and configurable 6G design is necessary. Balancing flexibility, performance, complexity, and cost efficiency is a key design challenge for 6G systems.

3.1.1 Waveform

3.1.1.1 Overview

Waveform is a fundamental building block of every cellular generation. Waveform design involves selecting appropriate waveforms to transmit data over a communication channel, with the aim of maximizing spectral efficiency while minimizing interference with other wireless devices. The choice of waveform has a significant impact on the power consumption, data rate, dynamic spectrum sharing with 5G, and reliability of wireless communication systems.

In the 2G era, the Gaussian Minimum Shift Keying (GMSK) waveform was used. It applies a Gaussian filter to shape the modulated signal and generate a constant envelope waveform. 3G cellular systems adopted a Code-Division Multiple Access (CDMA) waveform for transmission, enabling multiple users to share the same frequency band using unique codes to distinguish their signals.

The 4G wireless network utilized Orthogonal Frequency Division Multiplexing (OFDM) for its DL transmission. OFDM is a multi-carrier modulation technique that divides the frequency band into multiple orthogonal subcarriers, each carrying a narrowband signal. For UL transmission in 4G, Discrete Fourier Transform spread OFDM (DFT-s-OFDM) waveform was adopted. This waveform is a modified version of the traditional OFDM waveform, where DFT spreading is applied to the modulated data, converting the data symbols into the time domain. Furthermore, both OFDM and DFT-s-OFDM facilitate simple receiver process with good performance, including channel estimation and equalization.

In 5G, OFDM was adopted for both DL and UL transmission due to its high data rates, improved spectral efficiency, and ease of implementation. The choice of OFDM for 5G was also motivated by the consideration of dynamic spectrum sharing with Narrowband Internet of Things (NB-IoT) and Cat-M. Additionally, DFT-s-OFDM waveform was adopted for UL transmission as a power efficiency option.

6G waveform design's primary goal is to improve the performance of cellular systems in various critical aspects, including high data rates, extended coverage, reduced latency, improved energy efficiency, reliability, spectrum sharing and coexistence with 5G, and cost and complexity reduction. Additionally, 6G waveform design is anticipated to leverage new frequency bands, such as sub-THz/THz frequencies, and facilitate JCAS, positioning, PHY security, and other use cases.

3.1.1.2 Challenges and Research Directions

6G waveform design should address the following challenges to meet the evolving needs of cellular systems:

> **High spectral efficiency:** Spectral efficiency is a critical consideration 6G cellular design because it measures how efficiently these systems utilize the available frequency spectrum to transmit data.

> **Ultra-high reliability and low latency**: 6G's ultra-low latency and ultra-high reliability requirements are driven by the growing demand for real-time applications and services that require instantaneous response and high reliability. Reducing latency necessitates shorter transmission time intervals, and waveform design plays a critical role in achieving this. A waveform with low implementation complexity and efficient signal processing can reduce the end-to-end latency of the communication system, enabling real-time applications and services. In addition, 6G waveforms should be designed to achieve ultra-high reliability to meet the requirement.

> **Massive connectivity:** Due to the proliferation of Internet of Things (IoT) devices and the rising demand for data-driven services, 6G networks are envisioned to support a vast number of connections with diverse traffic patterns, data rates, and latency requirements. To enable massive connectivity, 6G waveforms should be optimized to provide innovative multiple-access mechanisms, efficient resource allocation, and reliable transmission. In addition, the design of 6G waveforms should be flexible enough to cater to different types of devices with varying requirements and capabilities.

> **Low computation complexity:** This is a crucial 6G waveform design factor. By allowing for efficient implementation of signal processing algorithms with low computational complexity, 6G waveforms can help achieve lower power consumption and longer battery life, which are vital device requirements. In addition, high system complexity can limit the selection of 6G waveform candidates for specific applications, which can impact both cost and energy efficiency.

> **Power efficiency:** This has become an increasingly important consideration in wireless systems. When designing 6G waveforms, it is important to minimize the power consumption of wireless devices and network infrastructure including analog components and digital computation power while maintaining high spectral efficiency. For instance, waveforms with low PAPR can utilize Power Amplifiers (PAs) more efficiently, thus reducing power consumption.

In wireless communication, waveforms can be generally categorized as either single carrier or multi-carrier. For multi-carrier waveforms, candidate 6G waveforms include, but are not limited to, OFDM and its variants, such as peaky Frequency Shift Keying (FSK). For single-carrier waveforms, potential 6G waveforms include, but are not limited to, DFT-s-OFDM and variants, Single-Carrier Frequency-Domain Equalization (SC-FDE) waveform, Orthogonal Time Frequency Space (OTFS) and its variants, and ultra-low complexity waveforms.

3.1.1.2.1 Multicarrier Waveforms

OFDM and Its Variants

OFDM was adopted as the basic transmission waveform in Long-Term Evolution (LTE). Multipath is a typical phenomenon in a wireless channel, so a Cyclic Prefix (CP) is inserted in every OFDM symbol to help isolate interference from adjacent symbols. This is referred to as Cyclic Prefix - Orthogonal Frequency Division Multiplexing (CP-OFDM) waveform. Isolating interference between OFDM symbols significantly simplifies receiver implementation, especially in the MIMO case.

There are, however, two major drawbacks in OFDM: high PAPR and slow spectral roll-off. The PAPR problem can be partially addressed by introducing DFT spreading, resulting in a waveform of essentially single-carrier characteristics. This is referred to as DFT-s-OFDM waveform and is discussed further below. The slow spectral roll-off issue results from rectangular time-domain pulse shaping, which has a frequency roll-off rate as slow as . The roll-off rate can be increased by spectrum shaping filtering or time-domain windowing. However, there is a trade-off between time-domain and frequency-domain isolation, and there might be impact on latency and complexity.

5G NR continues to adopt OFDM as the basic transmission waveform in conjunction with implementation enhancements to control the spectrum emission (e.g., filtering and windowing or Weighted Overlap and Add (WOLA)). It has been shown that OFDM with efficient implementation can achieve similar spectrum emission property to other multicarrier waveform proposals, such as Filter Bank Multi-Carrier (FBMC), Generalized Frequency Division Multiplexing (GFDM), Universal Filtered Multicarrier (UFMC), etc., which entail much higher receiver complexity and are more difficult to work together with MIMO. In fact, motivated by the ease of coexistence and spectrum sharing between LTE and 5G NR, 5G NR includes an OFDM numerology that is identical to LTE's. 5G NR further exploits the scalability of OFDM numerology to make it suitable for operating at new spectrum, especially in cases where the carrier bandwidth is much wider or operating at a higher frequency. In addition to the 15 kHz subcarrier spacing adopted in LTE, NR Release 15 also includes 30, 60, and 120 kHz subcarrier spacings. The 120 kHz subcarrier spacing supports a carrier bandwidth up to 400 MHz. Release 17 introduced 480 KHz and 960 kHz subcarrier spacings to support NR operation beyond 52.6 GHz. With 960 kHz subcarrier spacing, the largest supported carrier bandwidth is 2 GHz.

For 6G, two additional important considerations are coexistence and spectrum sharing with an earlier generation and possibly supporting an even larger carrier bandwidth. Similarly, the aforementioned issues such as PAPR and spectral roll-off need to be considered jointly with 6G spectrum, architecture, and use case considerations. For sub-THz, it is advantageous from the power amplifier efficiency point of view to consider a waveform with single-carrier properties for both UL and DL. Furthermore, with the increase of many radio branches in massive MIMO systems, efficient PAPR-reduction techniques are an active area of research.

CP-OFDM and DFT-s-OFDM, as specified for LTE and 5G NR, are still strong candidates for 6G waveform choices. It is beneficial to research the implementation of CP-OFDM transmitters to see whether it is possible to generate OFDM waveforms at a lower complexity than the conventional DFT and FFT approach without compromising the coexistence and spectrum-sharing considerations as mentioned above. Furthermore, the use case requirements for sensing and zero-energy devices are very different than those for eMBB. An interesting research problem is how the OFDM waveforms can be adapted for sensing and zero-energy devices, taking use case requirements, transceiver architecture compatibility, and spectrum sharing and coexistence jointly into design consideration.

Peaky FSK

Previously used signaling schemes such as CDMA and OFDM fail in energy-limited regimes, where the average signal-to-noise ratio (SNR) is small due to the fact that low energy per Hertz implies the lack of Channel State Information (CSI) [1] [2] [3]. In these energy-limited regimes, reliable CSI cannot be obtained due to fourth moment constraints [1], [2]. This lack of CSI is detrimental to the rates of CDMA and OFDM.

It has been shown that signaling schemes that are concentrated in both time and frequency will perform well in this regime without CSI [4]. These signaling schemes incorporate a duty cycle with the frequency concentrated signal, which increases the peak transmit SNR while maintaining the average transmit SNR constraint. Impulsive Frequency Shift Keying (I-FSK) [4] [5] [6] and Wideband Time Frequency Coding (WTFC) [7] are examples of such signaling schemes. Figure 1a depicts an I-FSK signal, which is the time period in which the FSK signal is transmitted is known to both the transmitter and the receiver, and outside the transmit period, the transmitter is silent. Figure 1b depicts a WTFC signal, which is similar to I-FSK, except the time period in which the signal is transmitted is only known to the transmitter, allowing information to also be encoded in the transmit time period.

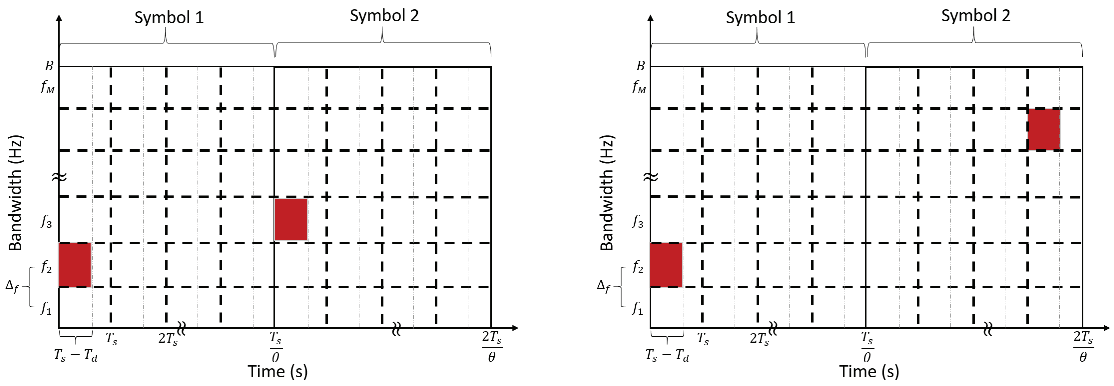


Figure 1 - Depictions of 1a) I-FSK modulation and 1b) wideband time frequency coding.

I-FSK has been shown to achieve the Additive White Gaussian Noise (AWGN) capacity in the infinite bandwidth and zero duty cycle limit [5], while also performing well in the finite bandwidth and non-zero duty cycle regime [6]. It has also been shown to be robust in challenging channels with high delay and Doppler spread, which may arise due to urban environments and high-speed movement, and outperforms OFDM and CDMA under these conditions [7]. This can be seen in Figure 1b. Furthermore, there have been promising over-the-air test results showing that the experimental performance of I-FSK aligns well with the theoretical model of I-FSK while operating under Federal Communications Commission (FCC) constraints for max transmit power and bandwidth. These show its potential in real-world systems [8].

3.1.1.2.2 Single-Carrier Waveforms

DFT-s-OFDM and Its Variants

Discrete Fourier Transform Spread OFDM (DFT-s-OFDM) is a waveform design that spreads the modulation symbols using DFT before mapping them to the CP-OFDM subcarriers for transmission. The DFT-s-OFDM signal exhibits a low PAPR compared to CP-OFDM, enabling more power-efficient operation, and is therefore adopted in LTE and NR for UL transmissions. Equivalently, DFT-s-OFDM can be viewed as a single carrier waveform with time domain pulse shape defined by the Dirichlet kernel. This view allows us to generalize the waveform by modifying the pulse shape using methods like Frequency Domain Spectrum Shaping (FDSS) or time domain filtering. Such generalized waveforms can be further enhanced as described below.

To reduce the waveform overhead, Zero Tail/Unique Word DFT-s-OFDM (ZT/UW-DFT-s-OFDM) was proposed [9] [10]. The design removes the CP of DFT-s-OFDM and replaces it with a pre-DFT guard period. The guard period could be padded with either zeros or a known sequence (unique word). This eliminates the abrupt transition between consecutive time domain symbols and thus reduces the spectral leakage and allows a smaller frequency guard band. In addition, the unique word could also serve as a reference signal for channel estimation, which further reduces the system overhead.

Another major branch of DFT-s-OFDM based signal designs focus on PAPR enhancements. These designs offer further PAPR improvements and could provide significant power-efficiency enhancement at low spectral efficiency region. Examples of these proposals include 1+D pre-coded DFT-s-OFDM with π/2-BPSK [11], Continuous Phase Modulated DFT-s-OFDM (CPM-DFT-s-OFDM) [12], and a more general trellis-coded DFT-s-OFDM (TC-DFT-s-OFDM) [13]. Each of these designs can be viewed as a combination of coded modulation and DFT-s-OFDM, as will be discussed in more detail in the modulation section. Depending on the modulation schemes, PAPR of DFT-s-OFDM could also be reduced via optimization of the FDSS. The enhancement has been adopted by NR for π/2-BPSK and is currently being considered for Quadrature Phase Shift Keying (QPSK).

Figure 2 illustrates a generic block diagram of DFT-s-OFDM-based waveforms as discussed above.

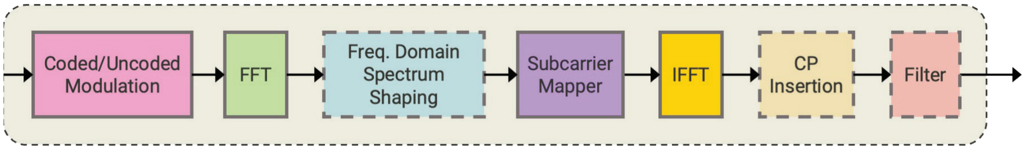


Figure 2 - A generic representation for various DFT-s-OFDM-based waveforms

SC-FDE Waveform

SC-FDE is a promising single-carrier technique for highly dispersive channels in broadband wireless communications. SC-FDE attaches a CP to the transmitted symbol to eliminate inter-carrier interference (ICI) and allows frequency-domain equalization at the receiver site. The overall transmit block diagram of SC-FDE is shown in Figure 3, where TDPS stands for Time Domain Pulse Shaping.

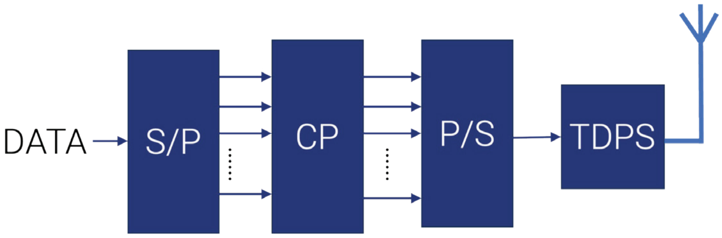


Figure 3 - SC-FDE transmit block diagram

The complexity and performance of SC-FDE systems are comparable to those of OFDM while avoiding the drawbacks like large PAPR ratio, intolerance to amplifier nonlinearities, and high sensitivity to Carrier Frequency Offsets (CFOs) associated with multicarrier systems. However, SC-FDE systems may suffer from the limited frequency domain scheduling flexibility compared to OFDM system.

OTFS and Its Variants

OTFS introduced in [14] is a framework for communication and active sensing that processes signals in the DD domain. OTFS has been researched extensively in the past few years, and hundreds of peer-reviewed papers about OTFS have been published. Three key features of OTFS are:

- A compact and sparse DD domain parameterization of the wireless channel, where the parameters map directly to physical attributes of the reflectors.
- A waveform/modulation technique, matched to the DD channel model, that embeds information symbols in the DD domain.
- The relation between channel inputs and outputs is localized, non-fading and predictable, even in the presence of significant delay and Doppler spread. As a result, the channel can be efficiently acquired and equalized, delivering constant post equalization SNR across all information symbols in a packet.

There are two variants of OTFS, as shown in Figure 4. The variant that has been the focus of almost all research attention so far is the Multi-Carrier OTFS (MC-OTFS), where the DD domain information symbols are first transformed to the Time-Frequency (TF) domain (using the Inverse Symplectic Finite Fourier Transform (SFFT) or Inverse SFFT, and the resulting TF symbols are then converted to a TD transmit signal using the Heisenberg transform (which is essentially an OFDM modulator). This variant ([14], [15], [16]) is more aligned with the 4G/5G waveform.

The second variant ([17], [18], [19], [20]) is the Zak-OTFS, which uses the inverse Zak transform to convert information symbols mounted on DD pulses directly to the time domain for transmission (no CP overhead). It has been shown to practically approach capacity for high Doppler spread channels with better BER performance than MC-OTFS. Whether such an approach can be found for MC-OTFS will need further research.

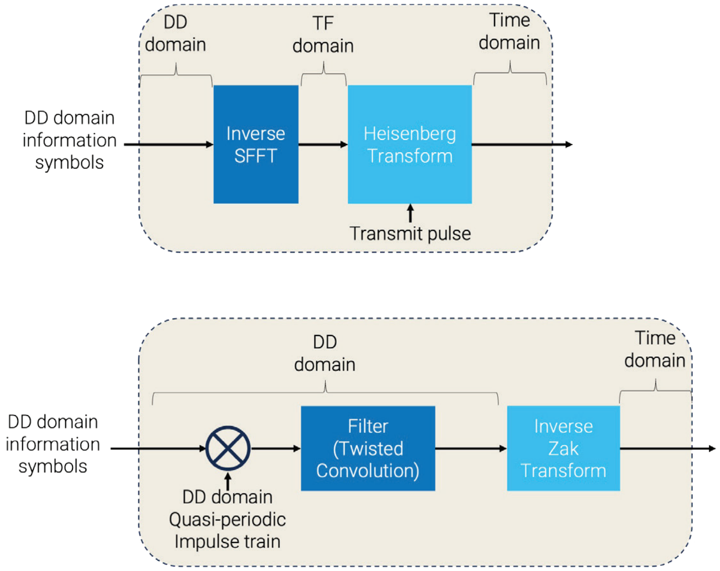


Figure 4 - A generic representation of MC-OTFS (top) and Zak-OTFS (bottom) transmitters

An important characteristic of the Zak-OTFS occurs when operating in the crystalline regime defined by the delay and Doppler periods of the DD domain being greater than the effective channel delay and Doppler spread, respectively: There is no aliasing, and the OTFS input-output relation is predictable and exhibits no fading. Due to its predictability, the I/O relation of a sampled communication system can be learned directly without the need to know the parameters of the underlying channel. This creates the possibility of a model-free mode of operation, which is especially useful when channel estimation is out of reach. In the context of radar sensing, operating in the crystalline regime with the proper selection of shaping filters reduces the ambiguity and increases the resolution among resolvable reflections.

Recent active research on OTFS has shown it as a promising technology for 6G. More research is underway and should continue to fully understand the system implications. The most relevant areas include MU-MIMO OTFS ([21], [22]), multiple access in the Delay-Doppler domain ([23], [24]), control channel design, and network implications necessary.

Ultra-Low Complexity Waveforms

To cope with the ever-increasing explosion of data traffic, 5G networks have significantly increased the number of antennas, carriers, transmission bandwidths, transmission points, and so forth when compared to previous generation networks. Concurrently, higher carrier frequencies have resulted in smaller transmission time intervals and altogether, 5G systems have seen an explosion in complexity through ever-increasing dimensionalities in time, frequency, and space. Especially in the physical layer and front end, including data conversion and beamforming, this increase in processing need, led to significantly increased complexity and energy consumption. Waveform design can thus play a crucial role in counteracting these effects on processing needs, complexity, and energy consumption thereby improving both 6G system cost and energy efficiency in terms of capital and operational expenditures.

Specifically, trade-offs between various KPIs — such as spectral and energy efficiency, and implementation complexity — are expected to crucially depend on the use case, frequency range, and other operational parameters. The 6G system, including the waveform design, should allow for these trade-offs and adapt to a chosen operating point with a specific set of performance requirements. For example, depending on the use case, bandwidth, frequency range, number of antennas, and other factors, the waveform may not always be chosen for utmost spectral efficiency with high degrees of linearity. Instead, relaxed requirements and high degrees of non-linearity may be desirable, such as to lower complexity, component cost, or energy consumption, or in some cases simply enable a technology such as fully digital beamforming with massive numbers of antennas. Specifically, this non-linearity and relaxation of requirements could be the consequence of low-resolution data conversion to simultaneously enable massive numbers of antennas and massive numbers of analog-to-digital/digital-to-analog data converters unlike the hybrid architecture of 5G massive MIMO systems that employ RF beamforming with a small number of data converters (cf., digital ports). By significantly reducing the cost of one digital transceiver chain and by affording each antenna its own digital transceiver chain, the hope is that distortions — and especially out-of-band emissions resulting from the non-linearity and relaxation — can be overcome through unprecedented numbers of antennas, enabled by the low-complexity nature of each digital transceiver chain, as well as novel coding techniques.

Waveforms that have been proposed in this context include Binary Phase Shift Keying (BPSK), Differential Phase Shift Keying (DPSK), and On-Off Keying (OOK). At the transmitter side, these 1-bit waveforms result in a carrier with phase +/-π or two amplitudes with a significant modulation depth of several tens of dB. The challenge is to modulate the carrier at several Gbps in an efficient manner. All signal processing is entirely in the 1-bit domain, and the digital output can immediately create the waveform. As a result, energy consumption and complexity can be reduced significantly and fully digital, ultra-low complexity, ultra-low power transmitters become a reality even with highly massive antenna deployments. At the receiver side, the main difference between BPSK, DPSK, and OOK waveforms is the need for a local oscillator. In the case of OOK, for example, the receiver becomes a simple threshold detector and can again directly be interfaced with the digital I/O.

Research challenges for ultra-low complexity waveforms include:

- Mitigation of adjacent channel leakage and out-of-band emissions.
- Pulse shaping and waveform design.
- Time/frequency synchronization and reference signal design.
- Novel coding techniques that can help lower out-of-band emissions in addition to traditional KPIs.
- Precoding and equalizer design.
- Fabrication of the antenna arrays and circuitry to make the promise of ultra-low cost, ultra-low power, fully digital, massive MIMO a reality.

It is furthermore expected that AI/ML techniques will play a crucial role in dealing with the non-linearity introduced by such waveforms.

3.1.1.3 Conclusion

6G waveform design will need to strike an appropriate balance between various design factors, such as high spectral efficiency, low computation complexity, and power efficiency to meet the demands of 6G wireless systems. It is also expected to enable new use cases such as JCAS, positioning, zero-energy devices, etc.

3.1.2 Modulation

3.1.2.1 Overview

Digital modulation, together with waveform and channel coding, plays a key role in defining how information bits are mapped onto a complex baseband signal before it is upconverted to the carrier frequency for transmission. Partitioning between these three blocks can occur in various ways. For example, Coded Modulation (CM) incorporates the idea of coding into modulation design to achieve better performance. Bit-Interleaved Coded Modulation (BICM), on the other hand, separates the design of channel coding and modulation to offer certain performance and complexity trade-offs. Specifically, channel- coded bits are mapped independently onto low dimensional constellations like QAM or Phase Shift Keying (PSK), allowing low complexity demodulation without much performance degradation. This is a major reason why BICM has been adopted in many modern communication systems such as LTE and NR. The boundary between modulation and waveform is even harder to define. As an example, continuous phase modulation (CPM) can be categorized as a constant-envelope waveform with partial-response encoding of phase transitions. Toward 6G, we envision a highly integrated and unified design of these three blocks, as the digital modulation work jointly with waveform and channel coding to provide enhancements corresponding to KPIs such as spectral efficiency, power efficiency, cost efficiency, and cell coverage.

For spectral efficiency enhancement, scaling up the QAM modulation order serves as the basic upgrade of modulation design that also helps to define the peak throughput of 6G systems. In addition, multiple constellation-shaping technologies have been proposed to achieve the shaping gain as predicted by the information theory. This typically involves joint design of low dimensional constellations (e.g., QAM or other 2D constellations) and shaping codes (e.g., Huffman codes or trellis-based shaping codes) that is used to shape the probability distribution of the modulated symbols. In general, these proposals can be viewed as coded modulation schemes that attempt to realize the shaping gain. Coded modulation also plays a key role in signal overhead reductions, as will be described in the following subsections.

For power efficiency enhancement, low-PAPR signal design has long been a major research area. These signals allow Power Amplifiers (PAs) to operate with maximized efficiency while suffering minimum performance and spectral impacts and are therefore suitable for scenarios that require optimized power efficiency. A low-PAPR signal also contributes to cell coverage and cost efficiency enhancements because it provides extended transmission range and could help reduce the number of base stations required. The design of low PAPR signals typically involves both waveform and coded modulation, as in the case of CPM described earlier. In fact, many low-PAPR design proposals for 6G can be viewed as combinations of coded modulations with time domain waveforms that allow flexible time-frequency resource allocations and simple receiver architectures (e.g., DFTS-OFDM). The role of the coded modulation in these proposals will be described in the following subsections.

3.1.2.2 Challenges and Research Directions

3.1.2.2.1 Low Dimensional Modulation Constellation Designs

QAM has been one of the most commonly used modulation schemes in wireless communication systems. Together with Gray mapping, which maps input bits to QAM symbols, it provides a regular, scalable constellation design that allows high spectral efficiency operations. In 5G NR, QAM modulation orders of up to 1024 are supported. To meet the peak throughput requirement for 6G, it is necessary to further scale up the constellation size (e.g., 4K-QAM). Operating at peak spectral efficiency with these high-order QAM modulations is quite challenging. Reliable communication in this case requires an SNR of over 30 dB and could not be achieved easily in many practical scenarios. Other impairments, such as phase noise and PA nonlinearity, further add to the complications. In a MIMO system, the complexity of QAM demodulator is a key design issue. As we increase the MIMO dimension and QAM modulation order for higher spectral efficiency, the receiver complexity increases, particularly for advanced demodulators like sphere decoders. Finding the optimized trade-off between spectral efficiency, performance, and demodulator complexity is a key research topic for 6G.

While typical QAM modulation is defined over the 2D integer grid with uniformly distributed modulated symbols, other non-evenly-spaced, non-uniformly-distributed modulation designs have been proposed for further enhancement. Such designs attempt to approach the optimal channel input distribution that achieves the channel capacity under certain constraints (e.g., average power constraint and peak power constraint) and are typically referred to as constellation shaping. The task of constellation shaping can be further decomposed into geometric shaping and probabilistic shaping. Geometric shaping aims to design a proper set of constellation points on the low dimensional I-Q plane, whereas probabilistic shaping strives to achieve the target (typically non-uniform) distribution on the designed constellation points. In fact, it has been shown that for a complex Gaussian channel with both peak and average power constraints, the optimal distribution is continuous and uniformly distributed in phase and consists of finitely many concentric energy levels with non-uniform probability.

For geometric shaping, circular Amplitude and Phase Shift Keying (APSK) constellations are typically used. These are constellation designs that have various amplitude levels (possibly non-uniformly spaced), forming multiple circles in the 2D complex plane. For each amplitude level, multiple constellation points are uniformly placed on the corresponding circle. With proper design of amplitude levels and number of constellation points on each corresponding circle, considerable shaping gain could be obtained. When probability shaping is applied jointly with geometric shaping (see next subsection for more details), capacity approaching spectral efficiency could be achieved. Note that the optimal constellation design for geometric shaping depends on SNR and the corresponding optimal input distribution. Finding a finite, manageable set of APSK modulations that could support near optimal performance for a wide range of SNRs is a key design issue for geometric shaping. Bit-to-symbol mapping is also a critical component in geometric shaping. In a coded system (e.g., BICM), the mapping affects the overall performance and impacts receiver complexity. In the case when probabilistic shaping is applied, the bit-to-symbol mapping is defined across multiple symbols via a shaping code, which further increases receiver complexity. Optimization of bit-to-symbol mapping in terms of trade-offs between performance, complexity, and its capability to work with other blocks is an important topic for 6G modulation design.

3.1.2.2.2 High Dimensional Coded Modulation Designs: Probabilistic Shaping and Index Modulation

To achieve channel capacity, the optimal distribution of the constellation symbols is generally non-uniform. Probabilistic shaping boosts the spectral efficiency via "shaping" of the effective distribution of the constellation symbols toward an optimized distribution. For this purpose, a shaping code (typically nonlinear) is applied across multiple 1D or 2D constellation symbols, forming an equivalent coded modulation scheme. Probabilistic shaping could be applied to any constellation design, including typical QAM constellations and APSK constellations constructed via geometric shaping. Shaping gain of up to 1.53dB could be observed for QAM constellations, as shown in Figure 5.

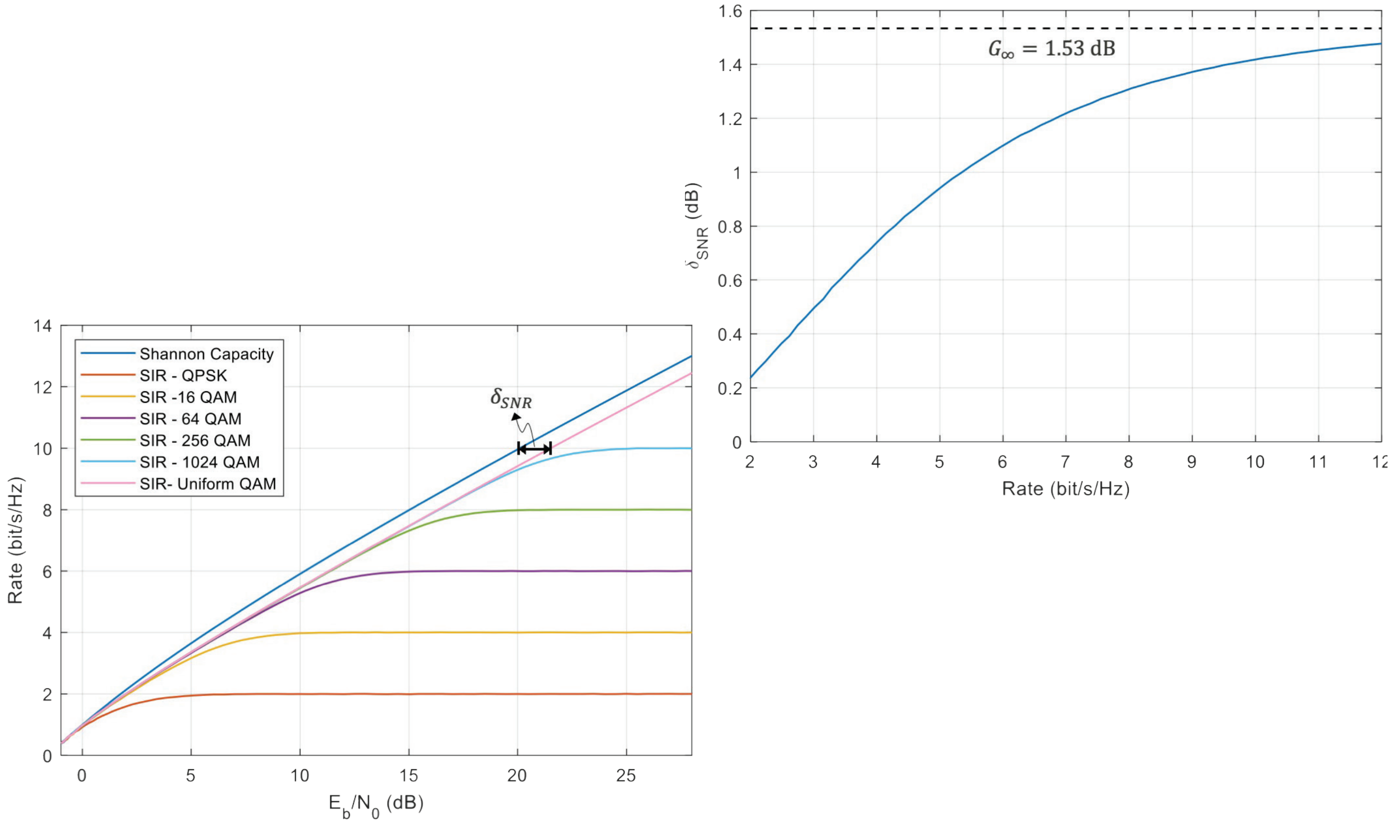


Figure 5 - Achievable shaping gain for QAM constellations

Various probabilistic shaping methods have been proposed. Trellis shaping [25] uses a convolutional code as shaping code to minimize the average power of the constellation symbols. This leads to a marginal distribution that approaches sampled Gaussian, and significant shaping gain could be obtained. Shell mapping [26] is another classical probabilistic shaping scheme. It partitions the constellation points into “shells” corresponding to various average power levels. A block code is used to select the shell indexes that result in minimized average power of constellation symbols. Like trellis shaping, considerable shaping gain could be achieved using shell mapping, which is adopted in ITU-T V.34 for spectral efficiency enhancement. Probabilistic Amplitude Shaping (PAS) [27] uses a distribution matcher to transform uniformly distributed bits into constellation amplitudes with the desired distribution. The distribution matcher used in PAS is a fixed-length-to-fixed-length mapper based on arithmetic coding. This allows efficient bit-to-amplitude mapping at the transmitter. Variable length distribution matchers could also be used in probabilistic shaping (e.g., distribution matcher based on Huffman code). However, these matchers pose challenges in data scheduling and resource management, and may require extra overheads (e.g., bit padding) when constructing the shaped symbols. Receiver design for variable length distribution matcher is also challenging due to error patterns that may include bit insertions and deletions. In such cases, a generic decoder (e.g., Ordered Statistics Decoding (OSD) [28] or Guessing Random Additive Noise Decoding (GRAND) [29]) could be used to correct the error patterns and decode the shaped bits.

For all the probabilistic shaping schemes described above, receiver complexity is a major design challenge. To approach capacity achieving distribution, the code length of the shaping code or distribution matcher needs to be sufficiently long. Furthermore, joint operation between the shaping code decoder and channel code decoder may be necessary to achieve optimum performance. The fundamental trade-off between performance and receiver complexity for probabilistic shaping needs to be carefully studied for 6G applications.

Index modulation [30] is a modulation scheme that carries information on the index domain. The indexes could be subcarrier indexes in a multi-carrier waveform or antenna indexes in a MIMO system. The information carried by the indexes is in addition to the information carried by the transmitted symbols. Therefore, spectral efficiency could be enhanced via index modulation. In general, index modulation can be viewed as a coded modulation scheme, where the underlying constellation is constructed by adding the “origin” to the original set of constellation points, and the modulation code depends on possible constraints of information carrying indexes. For example, if index modulation is applied to subcarrier indexes of the CP-OFDM waveform with a constraint that only a single subcarrier is used for transmission for each symbol, then it is equivalent to Multiple Frequency Shift Keying (MFSK), which is a form of orthogonal coded modulation. MFSK allows simple, power-efficient transceiver implementation, and is suitable for 6G applications such as MTC and Industrial IoT.

3.1.2.2.3 Modulation Designs for Power Efficiency Enhancement and Signal Overhead Reduction

Low-PAPR signals enable efficient PA operation, which is essential to achieve 6G sustainability. These include classical designs such as CPM and DFT-s-OFDM, and new proposals like CPM-DFT-s-OFDM [12], Trellis-Coded DFT-s-OFDM (TC-DFT-s-OFDM) [13], and Zero-Crossing Modulation (ZXM) [10]. In general, these low-PAPR signal designs can be viewed as combining (coded) modulation and single-carrier waveform, of which the coded modulation is designed to minimize the signal power fluctuations. In CPM-DFT-s-OFDM, time samples of a classical CPM signal are modulated by the DFT-s-OFDM waveform. The time-domain CPM samples can be described by a trellis-coded modulation (TCM), where the input bits are mapped through a trellis code to complex constellation points on the unit circle (i.e., PSK constellation points). With proper sampling rate, the trellis code ensures that the trajectory of the output signal of CPM-DFT-s-OFDM moves along the unit circle, leading to a low PAPR signal design. TC-DFT-s-OFDM generalizes CPM-DFT-s-OFDM by allowing other TCM designs and could achieve a better trade-off between signal PAPR and performance. π/2-BPSK followed by a 1+D precoder [11] is an example of such TCM design that offers both low-signal PAPR and robust performance when modulated by DFT-s-OFDM. ZXM uses a trellis-based run-length code to constrain the phase transitions between consecutive QPSK symbols before modulating it onto a single-carrier waveform. This TCM design effectively lowers the signal PAPR and makes ZXM a power-efficient waveform candidate for 6G.

Coded modulation can be used to shape the spectral property of the signal. In fact, the coded modulations used to construct low-PAPR signals described above also suppress signal sidelobes and reduce out-of-band (OOB) leakage of the signal. This implies a smaller guard band and improved spectral efficiency. Similarly, a linearly coded modulation is used in UW-DFT-s-OFDM for tail suppression when constructing the CP-less signal [10]. This reduces interference to the pilot (i.e., unique word) and allows better synchronization and channel estimation.

3.1.2.3 Conclusion

Digital modulation is a fundamental building block for any communication system. Classical schemes like QAM provide a baseline for 6G modulation design. For spectral efficiency enhancement, scaling up the QAM modulation order serves as the basic upgrade of modulation design that also helps to define the peak throughput of 6G systems. In addition, multiple constellation-shaping technologies have been proposed to achieve the shaping gain as predicted by the information theory. Index modulation can also boost spectral efficiency by carrying additional information in the index domain. For power-efficiency enhancement, various coded modulation schemes have been proposed, in conjunction with single-carrier waveforms, to form low-PAPR signals that allow efficient PA operations. Coded modulations can also be designed to reduce OOB leakage and signal overheads. In summary, moving onward to 6G, we envision the digital modulation block to work jointly with waveform and the channel-coding blocks to drive potential enhancements in spectral, power, and cost efficiency, and in cell coverage.

3.1.3 Channel Coding

Coding plays a critical role in achieving efficient and reliable communication over noisy channels. The fundamental limits of coding and communication were characterized by Shannon in his landmark 1948 paper. Since then, the central objective for coding is to design efficient encoding and decoding methods that could approach the fundamental limits established by Shannon. In the past 30 years, significant advances have taken place toward achieving this goal.

3.1.3.1 Historic Survey of Channel Coding

The first few decades of the field of channel coding were dominated by algebraic codes. The earliest algebraic codes appeared in the literature are Hamming, Golay, and Reed Muller, which have played important roles in deep space communications in the 1970s and 1980s. Reed Muller code also found applications in recent cellular systems (e.g., 3G Universal Mobile Telecommunications Framework (UMTS), LTE, 5G NR) to transmit very small control packets. Another important development in algebraic codes was the invention of BCH codes and Reed-Solomon codes. Both codes are widely used in practical communication and data storage systems, as well as used as outer codes in concatenated coding systems.

Cellular system went through a few generations of coding upgrades. Convolutional code was a natural choice for early generation cellular standards because it allowed easy application of Maximum Likelihood Decoding (MLD) techniques (via the Viterbi algorithm). Turbo codes, introduced in 1993 by Berrou, et al., were the first family of codes that achieved near-Shannon-limit performance with a practical decoding algorithm. Turbo codes were first introduced in 3G UMTS and later stayed in LTE standards, with an enhanced contention-free interleaver to facilitate high-throughput implementation. Low Density Parity Check (LDPC) codes were first introduced by Gallager in 1963 and rediscovered in late 1990s, shortly after the invention of Turbo codes.

LDPC codes have been adopted into a few wireless standards, including Institute of Electrical and Electronics Engineers (IEEE) 802.11, Digital Video Broadcast (DVB), and Advanced Television System Committee (ATSC). For cellular systems, LDPC recently replaced Turbo codes and became the channel coding scheme used in 5G NR data channels, driven by the high throughput requirement for 5G systems.

Polar codes were introduced by Arikan in 2008 as a family of capacity-achieving codes over Binary-Input Memoryless Symmetric Channels (BMS) with efficient encoding and decoding algorithms. The main idea of polar codes is to apply channel polarization transform in a recursive fashion and carefully selecting information versus frozen bits in U domain, in combination with two other powerful ideas — list decoding and Cyclic Redundancy Check (CRC) concatenation — polar codes were shown to perform better than tail biting convolutional code and adopted in 5G NR as the channel code for the control channel.

3.1.3.2 Decoding of Channel Codes

Modern channel codes often utilize soft-input decoding algorithms, where the demodulated symbols are converted into reliability information. This soft-input reliability information is then typically refined via iterative decoding or is used to generate a set of candidate outputs using list decoding.

In the case of Turbo codes, the process of one convolutional decoder generating the extrinsic information, which is then interleaved and passed to the other decoder, which in turn generates its extrinsic information and forms an iteration. Multiple iterations are performed until either a maximum count is reached or a check (e.g., CRC), passes.

Similarly, LDPC decoders are also most commonly iterative. A belief propagation algorithm is used where variable nodes exchange messages with check nodes. The order in which node messages are updated affects convergence speed. For example, a flooding schedule, where variable nodes and check nodes are updated in parallel, generally has the slowest convergence in terms of number of iterations. On the other hand, a layered decoding schedule, which sequentially visits check nodes and updates each node's inputs and outputs before proceeding to the next, generally requires half as many iterations as a flooding schedule. Using a small number of iterations on average reduces the decoder power consumption in typical use. Generally, the average is significantly lower than the maximum iteration limit, and we note that increasing the maximum numbers of iterations can be achieved without changing the decoder hardware implementation. The parallelism of an LDPC is highly scalable: It can start from a single edge of a single check node, to all edges of a check node, to multiple check nodes, to a fully parallel implementation. Using quasi-cyclic LDPC codes adds another level of parallelism where each edge contains multiple messages that are updated in parallel. Check nodes corresponding to orthogonal rows in the parity check matrix can be updated in parallel without changing performance at a given number of iterations.

List decoding, as applied to polar codes plus an outer CRC concatenation, is an efficient way to achieve good performance for small to medium block length. Decoding of polar codes sequentially estimates bits. As such, it may be challenging to implement list decoding with low latency and high parallelism. One way to increase the decoder parallelism is to decode at the constituent code level instead of always decoding at the bit level.

In addition, there are decoding schemes applicable to general binary linear block codes, such as OSD, Box and Match Algorithm (BMA), Adaptive Belief Propagation (ABP), and more recently GRAND, which can be applicable to any block code with moderate payload size or redundancy, regardless of structure. GRAND can be used for hard or soft information decoding, the latter partly with Ordered Reliability Bits (ORB) GRAND.

3.1.3.3 Outer Code & Network Coding

In addition to PHY layer coding, channel coding has its usages beyond PHY layer FEC, with potential applications across the air interface protocols. One example is in the form of inner code and outer code that integrates the Flexibility of Network Coding (FEC) (e.g., network error correction codes, network erasure codes) for diverse deployment scenarios such as wireless point-to-point and mesh topologies, etc. This is mainly aimed to address the inefficiencies in the channel coding and retransmission protocols at the physical/Media Access Control (MAC) layer in use cases in which a feedback channel to acknowledge the transmission is either difficult to have or difficult to scale. This additional coding flexibility will be important to address new application use cases that demand both the high data rate of eMBB and the low latency and high reliability of Ultra Reliable and Low Latency Communications (URLLC).

As the network topology of cellular systems continues to evolve, it is expected that 6G may support a more distributed topologies than point to point connecting a diverse set of node types such as small cells, IAB, smart repeaters, RIS, etc. These distributed topologies constitute a momentum for the use of upper layer coding. One option for this is network coding for a better resource efficiency and reaching higher network capacity. Another is outer coding in the dual/multi connectivity cases as a replacement to Packet Data Convergence Protocol (PDCP) duplication in order to leverage link diversity and enhance reliability with reduced delays compared to the exclusive use of retransmissions protocols. Introducing coding components into distributed multi-hop and multi-path topologies constitutes a potential for improving end-to-end trade-offs between energy efficiency, deployment complexity and network performance.

In addition to distributed deployments for mmWave and sub-Terahertz networks, private networks can also experience dynamic traffic flows and topologies because a node can alternatively communicate, sense or becoming idle while exchanging multiple content on different segments. This can occur in the network-enabled devices (such as robots) or in the distributed sensing and communication use cases. The introduced variability and diversity can reflect into novel protocols or code design for the 6G distributed topologies, illustrated in Figure 6.

3.1.3.4 Recently Trending Coding Topics

As research in coding continues to progress across academia and industry, a few new coding designs emerge, such as:

- As will be discussed in more detail in the multiple access section, Unsourced Random Access (URA) is a new multiple access framework that aims to accommodate the needs of uncoordinated random access from a massive number of users [31]. Novel coding designs (e.g., schemes inspired by compressive sensing [32]) for URA may be useful to improve the random-access capacity in 6G, as well as channel code for high spectrum efficiency scenarios.
- As an alternative to the commonly used pilot-assisted transmission schemes, noncoherent communication schemes aim to communicate over wireless fading channels without transmitting pilots (i.e., pilot-free). Code design for noncoherent communication may provide performance improvements over conventional pilot-assisted schemes with mismatched decoding in the short block length or low SNR regime with comparable complexity [33], [34].
- Semantic communication techniques target the efficient communication by exploiting the semantics of the communication, which were typically ignored in conventional communication system design. Coding for semantic communications may consider some joint source and channel coding designs to further enhance communication efficiency.
- Decoding enhancements for general linear block codes, as discussed in earlier section on decoding [28], [35], [36].
- Emerging fields for coding applications: new verticals, URLLC, sidelink, NTN where coding could play pivot roles in addition to FEC functionalities.

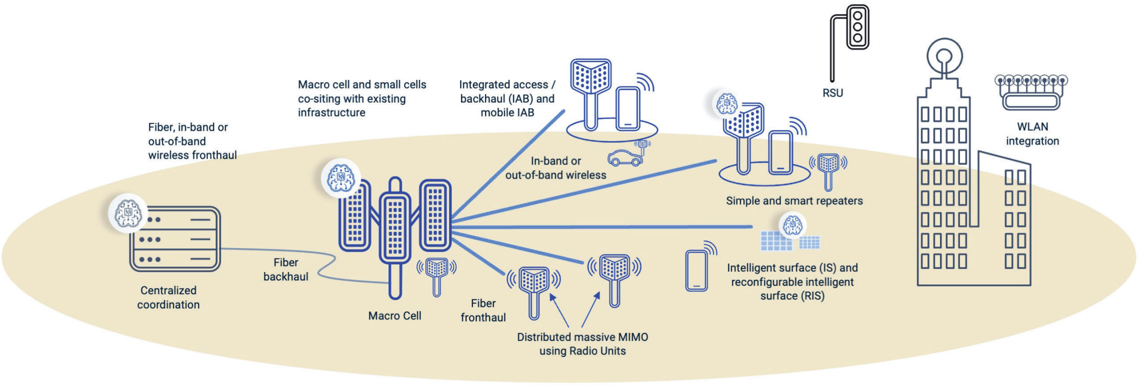


Figure 6 - Distributed network topology for 6G

3.1.3.4.1 New Requirements for 6G Coding

We envision channel coding to provide further enhancements corresponding to KPIs such as peak throughput, spectrum efficiency, power efficiency (Tx and Rx), area efficiency, processing latency, etc. For example, finding channel coding schemes that have favorable performance-complexity trade-offs may be an important research topic to support the higher peak throughput scaling for 6G, and to provide further enhancements over power and area efficiency. Coding/decoding schemes with lower processing latency can be useful for low-latency applications. Furthermore, channel coding may be jointly optimized with other fundamental blocks such as modulation, waveform, and MIMO to meet these requirements.

3.1.4 Multiple access

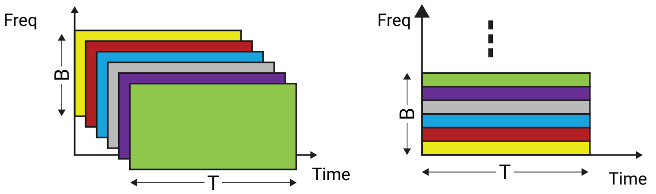
3.1.4.1 Overview of multiple access schemes

Multiple access design is at the center of every wireless generation. 6G waveform/multiple access technologies are expected to continue to evolve based on 5G waveform/multi-access schemes (as more frequency bands are introduced) to improve spectrum and power efficiency, and achieve more robust coverage in conjunction with other technologies, such as advanced MIMO and beam/CSI tracking schemes. Multiaccess design for massive MTC that can support high cell capacity and high user density is another interesting research direction to realize the intelligent connection vision of 6G. In this section, we give an overview of MA schemes and potential candidates for 6G new use cases and requirements.

3.1.4.2 State-of-the-Art Multiple Access Schemes

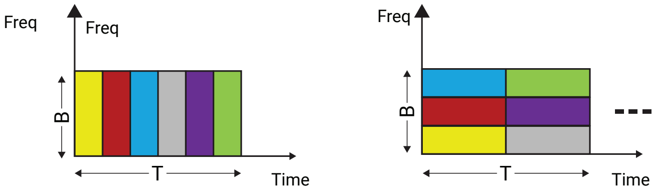
Spectrum is a precious resource for wireless systems. A scheduling-based multiple access framework is considered an efficient way to dynamically share spectrum resource across achieve high spectrum efficiency and high overall system capacity. The base station makes joint scheduling decisions and dynamically allocates resources to different users to achieve high statistical multiplexing gain, multiuser diversity gain, and multi-user MIMO spatial multiplexing gain over static resource allocation.

Time/frequency synchronization between the gNB and User Equipment (UE), and tighter power control, etc. are needed to improve overall spectrum efficiency and throughput. Efficient link adaptation, IR-HARQ, etc. schemes can be enabled under the scheduling-based MA framework to attain superior and robust performance against fading and bursty interference. As a result, scheduling-based MA can achieve full frequency reuse (instead of static frequency reuse) across the entire network deployment. In classic 3G, 4G, and 5G systems, time, frequency, code-division, spatial domains, and multiple access are all considered in conjunction with scheduling-based MA framework. Figure 7 illustrates some typical multiple access schemes.



(a) RSMA

(b) FDMA



(c) TDMA

(d) FDMA + TDMA

Figure 7 – Multiple access schemes

3.1.4.3 Uncoordinated Random Access

Scheduling-based MA requires some level of UE connection and scheduling overhead. For example, in 4G and 5G networks, regular scheduling-based MA needs to perform multi-step handshaking between the gNB and UE to set up the radio connection. This overhead becomes non-negligible in the scenario of large number of devices with infrequent, small, data bursts. In addition to the significant overhead that such a scheme could impose on a system, the connection procedure itself could become the main source of power consumption for the users with small data bursts. For small data communications, especially in the context of a massive number of users, some form of uncoordinated random access (URA, a.k.a., Contention-Based Random Access (CBRA)) may be more efficient as a complementary feature to scheduling-based MA.

In the context of 4G/5G, there are two categories of URA: semi-persistent scheduling (including UL configured-grant (ULCG) in 5G) and Physical Random Access Channel (PRACH) process, including both 2-step Random Access Channel (RACH) and 4-step RACH. It is worth mentioning that due to the uncoordinated nature of URA, the multiple access in the UL is likely to be NOMA. In contrast to scheduled Orthogonal Multiple Access (OMA), it is hard to guarantee orthogonality in ULCG and 2-step RACH Ues in both DMRS and data. Hence, NOMA becomes an essential component of both use cases. NOMA has been studied in 5G, and iterative joint Multi-User Detection (MUD) and decoding schemes have been evaluated as an enhanced transceiver architecture. A high-level block diagram of NOMA architecture is illustrated in Figure 8.

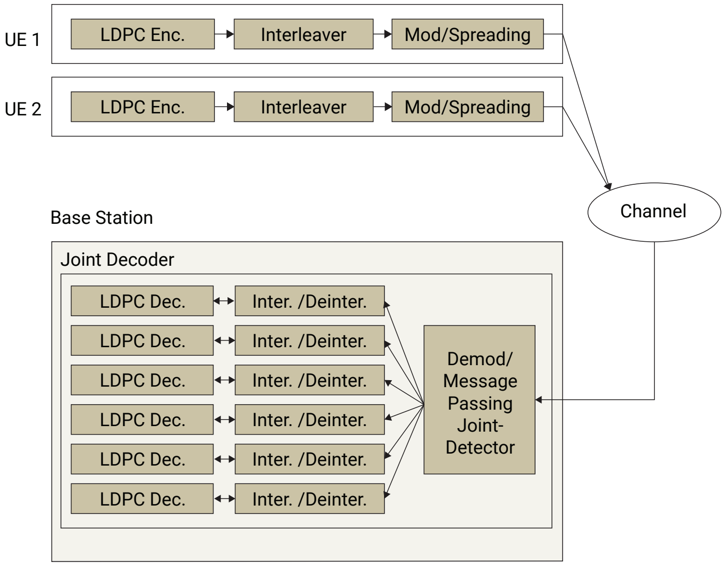


Figure 8 – An example of transmitter and receiver block diagrams for NOMA scheme

URA is a novel multiple access design recently introduced to accommodate the needs of large volume of uncoordinated random access. This formulation features a slotted framework where transmissions occur in frames. While the total device population is huge (potentially infinite), only a small subset of them is active during any transmission frame, and the active devices access a shared channel to convey their respective payloads to the central base station. URA problem setup has close connection to 5G NR PRACH procedure and provides new tools to boost random access capacity in 6G.

In the future 6G networks, the scheduling-based and contention-based MA schemes are expected to further co-evolve and complement each other.

3.1.4.4 Design Considerations for 6G

As we evolve into 6G, there are new technology/business opportunities and design challenges to meet 6G requirements. One need is a unified framework for multiple access and waveform multiplexing that supports key 6G KPIs (e.g., higher spectral/power efficiency, extended link budget, enhanced reliability with low latency, multiplexing efficiency across multiple users, coexistence between different users, robust high velocity performance) across large range of carrier frequencies, scalable with channel bandwidth, MIMO orders, and flexible enough to serve different verticals across DL/UL/SL, TN and NTN, communication and non-communication use cases.

Waveform/multiple access schemes are expected to evolve with and fit into other new advanced RAN technologies, such MIMO, CSI and beam acquisition/tracking, to substantially improve regular 6G mobile broadband performance and to provide 6G massive URA intelligent connectivity while achieving harmonic coexistence with other RATs (e.g., 5G, NB-IoT).

In addition to the classical use cases, potential new use cases and new verticals — such as XR/metaverse, massive IoT, side-link, massive spectrum aggregation across frequency ranges, flexible duplexing, UE cooperation, joint communication, positioning, and sensing, etc. — have attracted research interest in both academy and industry. Waveform/multiple access design for such new use cases is becoming one of the most active 6G research areas. Several potential 6G use cases are illustrated in Figure 9.

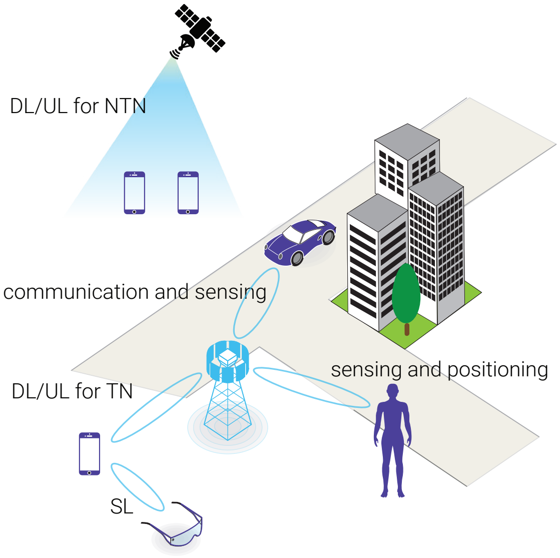


Figure 9 – 6G multiple access use case scenarios

Several factors may guide MA design for 6G. With the adoption of new spectrum bands and technologies such as advanced duplexing schemes, RF requirements may become more stringent in certain cases. It is worth mentioning that new duplexing schemes can be perceived as equivalent forms of MA schemes, as shown in Figure 7. Frequency Division Duplexing (FDD)/Time Division Duplexing (TDD) can be considered to conventional Frequency Division Multiple Access (FDMA)/Time-Division Multiple Access (TDMA), while full duplex could be considered as a form of Space Division Multiplexing (SDM) between UL and DL.

3.1.5 Conclusion

The vision for 6G multiple access design is twofold: to continue to enhance existing mobile services and to proliferate further into new applications that continue to emerge with the digital revolution. To support a wide range of use cases, 6G must incorporate several classes of multiple access schemes under a unified design framework. Traditional scheduling-based MA for high-data-rate, high-spectrum-efficiency use cases supplemented by URA to support scenarios wherein full coordinated scheduling is inefficient in terms of power and signaling overhead. Both orthogonal and non-orthogonal MA schemes are needed to achieve maximum spectrum efficiency and support large numbers of users with low overhead and high device power efficiency.

6G MA should consider spectrum efficiency, system resource utilization, UE and network power efficiency, processing complexity, etc. to ensure a healthy ecosystem evolution from 5G. With the introduction of new services beyond eMBB, URLLC and IoT, etc., new MA schemes are expected to enable efficient multiplexing of waveforms for communication and non-communication services (sensing, positioning, etc.).

3.2
Spectrum Sharing

New spectrum is essential for successful deployment of the next generation of mobile networks. Spectrum is, however, a limited resource that deserves efficient utilization. Exponential wireless traffic growth in the past 30 years has made it harder and harder to find greenfield spectrum suitable for mobile broadband. Sharing techniques have been proposed to alleviate the reduced availability of new spectrum for 6G. Sharing based on non-overlapping geography can be one of the simplest techniques but may fall short on goals of spectrum utilization and efficiency. New techniques that rely on various types of static and dynamic sharing over the same geographic area are receiving attention as a promising approach to secure more spectrum for 6G.

3.2.1 Overview

Spectrum reuse has been a fundamental principle in radio network planning and managing traffic growth in mobile networks. Today, the number of users and connected devices continues to grow exponentially at double-digit Cumulative Aggregate Growth Rates (CAGR) every year. To some extent, spectrum utilized by mobile services is always shared, but the modalities for sharing differ. Sharing among mobile service users associated with the same service provider is centralized and handled by one network. Going forward, sharing scenarios may also include co-existence with other services and networks due to the increasing scarcity of spectrum and complexity to relocate legacy equipment operating in bands targeted for 6G.

Figure 10 illustrates the various forms of sharing by charting the paths that relate the two major regulatory regimes constituted by licensed and unlicensed spectrum into realizations of spectrum sharing. In this document, we treat medium access control techniques, including scheduled transmissions or contention-based access such as Listen-Before-Talk (LBT) protocols as multiple-access techniques, acknowledging their role as effective sharing methodologies.

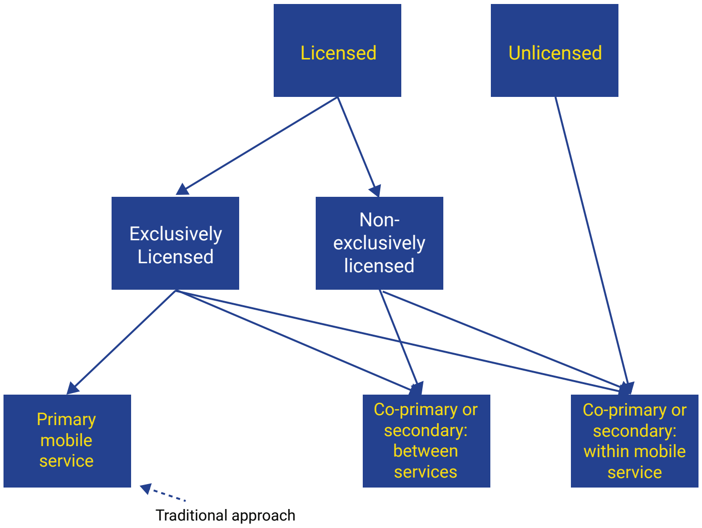


Figure 10 – A tree diagram illustrating the relationship between spectrum use and various forms of sharing; the boxes with yellow text depict typical regulatory mechanisms and implementation methodologies

The goal of spectrum sharing can be summarized into two related objectives: spectrum efficiency and spectrum utilization. Spectrum efficiency improvement is an engineering objective, whereas improved spectrum utilization is a policy objective that can be translated into engineering requirements. The result is a trade-off of conventional expectations on area spectral efficiency versus greater degrees of utility among autonomous uses. An additional aspect for practical spectrum sharing is system complexity. UE complexity issues may arise from the need to maintain reliable connectivity to the network.

The objective of this section is to address engineering decisions that may be driven by constraints placed on the various modes of spectrum access, regarding the performance objectives that will need to be met:

- **Ubiquity and quality of experience (QoE):** Wide-area public communications networks need available spectrum over large coverage areas for broad coverage of those services.
- **Incumbent presence:** Some spectrum suitable for 6G is in use by other services. The ability to share spectrum in co-primary or secondary scenarios is important to meet the demands for new spectrum.
- **Utilization efficiency:** When spectrum is allocated, one factor to consider is the tendency to require high utility from the assignment, without compromising spectral efficiency.
- **Dynamic sharing:** Some spectrum ranges are predisposed to sparse use by incumbents. Developing dynamic sharing techniques based on situational awareness of the radio environment may open new opportunities for 6G.
- **Application requirements:** Wireless networks are naturally capable of meeting high dependability requirements only with dependable spectrum allocation. But not all applications have extreme needs for data rate, spectrum reliability, and latency.

3.2.1.1 Sharing in Licensed Spectrum

Licensing provides for wide-area coverage whereby spectrum sharing within an operator's network maximizes the number of users, without compromising on performance and spectral efficiency. This is the primary motivation for exclusively licensed spectrum. Furthermore, licensed spectrum, whether exclusive or shared, enables higher reliability and better performance than spectrum that is unlicensed or licensed by rule. Such dependability is sought by business-critical use cases, and in what follows, we describe the advantages of sharing in licensed regimes.

3.2.1.1.1 Sharing in Exclusively Licensed Spectrum

While counterintuitive, most exclusively licensed spectrum is still shared. This is apparent if one considers an operator that has exclusive geographical access to the spectrum and arbitrates channel access between a number of simultaneous users. Advanced transmission schemes exploiting spatial techniques such as MIMO and beamforming, and the use of advanced signal processing techniques that allow interference mitigation and spatial signal processing, have enabled extremely high levels of spectrum utilization and spectrum efficiency, offering an upper bound to performance for other forms of sharing.

When deploying new Radio Access Technologies (RATs), given the scarcity of spectrum, frequency re-use may also be targeted within a single cell's geographical area to enable the new and legacy RATs to share the same spectral resources and possibly hardware. This form of Multi-RAT Spectrum Sharing (MRSS) enables smoother introduction of the new RAT without having to re-farm spectrum until device penetration of the new RAT increases significantly.

In the case of 6G MRSS, there may still be a need to allow for backward compatibility of frequency resources between the 6G waveform, 5G NR, and perhaps even 4G LTE. This is especially the case for 4G LTE Low Power Wide Area (LPWA) cellular IoT devices, which are expected to be in service long after LTE mobile broadband services sunset. 6G MRSS will not only have to strive to provide a coverage layer but also capacity; hence, MRSS is expected to enable sharing in a spectral- and power-efficient manner between RATs for both FDD and TDD bands.

Furthermore, there may be interference scenarios between clusters of cells employing different RATs. Neighboring clusters may, for example, exhibit limited degrees of coordination, highlighting the need for robust co-existence and interference-mitigation techniques. Detection and minimization of interference, including cross-link interference mitigation techniques within the UE and network, may be investigated further.

3.2.1.1.2 Sharing in Non-Exclusively Licensed Spectrum

In this scenario, the most important sharing regime occurs between mobile users and other services, (e.g., fixed services, fixed or mobile satellite users, radar, earth exploration, and passive sensing services). An early example of such sharing is in the 1695-1710 MHz band between cellular UL and the Geostationary Orbit Environmental Satellites (GOES). Other examples include sharing between the Citizen Broadband Radio Service (CBRS) tiers and naval radar or commercial Fixed Satellite Service (FSS) in the 3550-3700 MHz range, and sharing between 5G in the 3450-3550 MHz frequency band and radars. The former relies on separation in geography and time of use, with the aid of a geolocation database and a policy manager known as the Spectrum Access System (SAS) [37]. The latter is based on geographically separated cooperative planning areas or periodic use areas. Co-primary licensing between two or more services may require interference avoidance or mitigation techniques that are respectful of each service's performance requirements. If 6G licensees are secondary users in a band, protection of the primary user must be ensured. The 6G licensees may be susceptible to interference from the primary users in the same band and possibly blockage from the adjacent bands; hence capabilities for interference mitigation may be considered. 6G licensees also need to ensure that leakage into adjacent bands is low enough that primary users of the adjacent bands are not impacted. Knowledge of primary users' operational characteristics and parameters will substantially help in improving spectrum sharing and efficiency.

Geographical sharing via sensing and/or definition of dynamic exclusion zones that allow the highest degree of flexibility for provisioning services can be considered, as well. When dynamic temporal sharing is employed, it helps if 6G networks and devices can modify their operational parameters (frequency, bandwidth, power, beamforming, etc.) to minimize end user impact. One example of temporal sharing involves government radar systems, which may use the band relatively infrequently but require high degrees of protection and in some instances quick reaction time. This will require intelligent control of the radio resource parameters to enable dynamic techniques to address interference susceptibilities for incumbents while maximizing 6G spectrum utilization. Spectrum occupancy by government radar systems may be determined by sensing and/or a 6G network interface to access suitably defined Incumbent Informing Capabilities (IIC) [38]. IIC would facilitate sharing with systems that cannot be detected through sensing, including radio astronomy and remote sensing. IIC could also help bi-directional sharing in more general sharing scenarios where Federal users are allowed to access non-federal bands, as suggested in the Omnibus Spending Bill of 2018 [39] and the Commerce Spectrum Management Advisory Committee (CSMAC) Report on Bidirectional Sharing [40].

Some networks may be able to use the shared band as a capacity augmentation measure where reliable spectrum is always available as a fallback. Spatial techniques that exploit a large number of antenna elements may also be utilized to enable concurrent use of spectrum in the same geographical location, without the need to overly rely on dynamic temporal sharing. For example, spatial techniques offer potential to enable spectrum sharing between terrestrial networks and non-terrestrial networks (NTNs) by restricting terrestrial network emissions above the horizon and in the direction of the NTN receivers.

Spectrum may also be shared among 6G co-licensees. The 6G spectrum allocation would be to multiple licensees that would need to create a mode of operation that allows high utility without significantly compromising area spectral efficiency. At present, shared spectrum among co-licensees is exemplified by the CBRS which is a 3-tiered system of users with a Priority Access License (PAL) and General Authorized Access (GAA) users in addition to the incumbents. Specifically, there are typically no restrictions against simultaneously using the same co-channel spectrum among multiple CBRS GAA users.

The efficiency of shared access in 6G systems may benefit from greater network intelligence, including the moderation of medium access between shared-license holders. There is interest in examining the opportunities for machine learning to optimize medium and spectrum access in a shared license network so that spectrum utility is improved without excessive energy expenditure or increase in signaling, while still achieving reasonable spectrum efficiency for individual component networks. RAN sharing also allows operators to share spectrum and reduce expenses. The main drawback for operators that comes with RAN sharing is difficulty to differentiate services. Open RAN architecture with standardized interfaces between RAN components allows operators to share part of the RAN, such as the RU. This can create new opportunities for spectrum sharing without restricting each operator's ability to customize its services and compete. To further improve the spectral utilization and efficiency when sharing among 6G co-licensees, interference detection and mitigation should also be considered because the capability to detect and mitigate interference by either suppression and/or reconfiguration can improve end user experiences.

Spectrum could be allocated on a TDD basis as a form of interference management between adjacent geographic regions or adjacent bands. This technique is common for mobile services within a technology. As the need for spectrum across services increases, it could be considered for sharing across services and technologies, as well.

3.2.1.2 Sharing in Unlicensed Spectrum

Unlicensed spectrum access systems execute channel access protocols such as LBT, or sensing followed by time and/or frequency hopping in order to avoid interference to and from other systems. 3GPP-based technologies for unlicensed spectrum access include 4G LTE Licensed Assisted Access (LAA) and 5G NR-U both of which rely on LBT protocols and schemes. The non-3GPP technologies for unlicensed access include those based on the IEEE 802.11 family of standards, Wireless Personal Area Network (WPAN) systems such as Bluetooth, Zigbee, Ultra-Wide Band (UWB), and others. There is little or no cooperation among these unlicensed systems, at the cost of traffic collisions and sub-optimal spectrum efficiencies.

While 4G LTE LAA defines only licensed assisted access, 5G NR-U also includes standalone operation. Standalone operation is typically used in private deployments that provide high geographical spectrum efficiency with small cells and is complementary to licensed spectrum-access macro-cell structures. Whenever network densification and new use cases require higher geographical spectrum utilization, unlicensed 6G systems are expected to support this target through improvements in spectrum sensing, channel selection, and medium access procedures.

3.2.2 Challenges and Research Directions

The definition and deployment of 6G systems allows a re-examination of coexistence issues among legacy and new systems to improve upon current technology and to introduce new spectrum-sharing techniques that can avoid harmful interference and mitigate receiver vulnerability. In the context of uncoordinated spectrum sharing, 6G systems are expected to exploit high-precision spectrum shaping and advanced band-pass filter designs (similar to or better than those in 5G) to be robust toward adjacent channel interference. At the same time, there are policy challenges in the way legacy technologies address filter selectivity or interference resilience in accordance with the state of the art [41]. Some incumbents are passive RF systems, such as radio astronomy and remote sensing, which require a quiet RF environment to maintain satisfactory spectrum or system sensing and measurement performance. Passive systems are thus often sensitive even to interference from adjacent channels. Coexistence between active 6G and passive RF systems needs to be thoroughly investigated.

Coexistence of incumbent (or primary) and secondary (or non-primary) services presents several challenges. To constructively share the spectrum with incumbent systems, the secondary services may have to implement active spectrum sensing or utilize a spectrum sensing capability provided by a spectrum access system (e.g., 6 GHz Automated Frequency Coordination (AFC) server, CBRS SAS, or future enhancements) to avoid harmful interference with incumbent systems. The sensing function first determines the instantaneous spectrum utilization and channel access opportunity before communication commences based on the sensing result. Research challenges and opportunities include how to:

> Suppress interference to increase Signal-to-Interference-plus-Noise Ratio (SINR).

> Allocate time, energy, and bandwidth resources among the sensing and communications functions.

> Ensure fairness in the Dynamic Spectrum Access (DSA) decisions that maximize the chosen KPIs while providing reasonable protection to primary users.

The impact on 6G networks and devices could be that some operational parameters — such as frequency, bandwidth, power, beamforming, and others — need to be modified on a short-term basis to adapt to new radio environments. Spatial processing techniques can be employed to minimize interference to NTN, but more research is needed to determine whether NTN receivers can be adequately protected. New Interference Protection Criteria (IPC) and methods must be carefully designed to address problems like secondary-to-primary user channel uncertainty and spectrum sensing errors, which could significantly affect the primary user protection performance. Although individual UE processing capability is limited, the aggregated processing capability of a group of UEs can be substantial. Therefore, collaborative spectrum sensing and corresponding sharing mechanisms should be explored, as well.

Spectrum sharing among co-licensees could provide an opportunity to improve spectrum utilization. Research topics include improving shared access by means of network intelligence, including the moderation of medium use between shared-license holders. Machine learning could be utilized to optimize medium and spectrum access in a shared license network while addressing any privacy or operational security concerns that may exist. Examples include sharing among 6G co-licensees and bi-directional sharing between 6G and federal services, which would allow access to additional spectrum bands. RAN sharing could be utilized for spectrum sharing among co-licensees, but more research is needed to identify RAN architecture and procedures that give operators full flexibility to differentiate their services and share spectrum. Spectrum allocated to co-licensees may also be on a TDD basis. More research is needed to understand interference issues associated with spectrum allocation on a TDD basis and how much can such allocation increase overall spectrum utilization.

Unlicensed spectrum utilizes medium access protocols to prevent collisions among users and to manage interference. More research is needed to improve spectrum sensing, channel selection, and medium access procedures targeted for dense network deployments in unlicensed spectrum bands.

3.2.3 Conclusion

Semi-static and dynamic techniques to share spectrum among multiple services, service providers, and/or technologies within overlapping geographical regions have potential to improve utilization of spectrum. Further research is needed to ensure that these spectrum-sharing techniques do not lead to unacceptable degradation of service for the existing primary deployments or unacceptable service quality for new secondary or co-primary deployments.

3.3
Advanced MIMO technologies

3.3.1 Low FR1 Band Enhancements

3.3.1.1 Overview

Spectrum bands below 1 GHz, referred to here as low frequency bands, define the baseline coverage of cellular networks. Unlike the higher frequency bands that 6G is expected to expand into, low-FR1 bands have the advantage of exhibiting low propagation loss and low penetration loss, making them ideal for coverage and deep penetration. Low bands can, however, become a bottleneck as they are expected to cover an increasing number of users, with a relatively limited bandwidth availability: Low frequency bands get paired with higher bands with a very large bandwidth (e.g., mmWave, sub-THz). It is thus crucial for 6G to work on candidate technologies to improve the spectral efficiency of sub-1 GHz bands while considering those bands' design characteristics and challenges.

3.3.1.2 Challenges and Research Directions

As we design the next generation of cellular networks, low frequency bands continue to be crucial for serving many users in a wide coverage area. Realizing Massive MIMO gains in the sub-1 GHz bands is expected to have a major impact on widespread coverage and on the overall cost efficiency and energy efficiency of 6G systems, despite several design challenges that need to be overcome.

One of the biggest challenges is related to the practical feasibility of Massive MIMO at low frequency bands, due to the large antenna size and the half-wavelength distance requirements between the antenna elements. The form factor limitation poses a challenge on the adoption of Massive MIMO systems (e.g., > 64Tx) in traditional towers or base station locations for low frequency bands. Modular or distributed Massive MIMO deployments could overcome this form factor limitation; however, more challenges arise related to the feasibility, processing, and architecture complexities of such deployments. Synchronization and calibration methods are further revisited as we move away from a cell-based deployment to a cell-free deployment, with geographically distributed transmitting points and coherent joint transmission.

Another set of challenges relates to channel state acquisition, especially as we move to a distributed MIMO deployment with potentially non-uniform antenna arrays. The transmitting points need to accurately estimate the channel to realize massive (distributed) MIMO and serve a massive number of UEs. Relying on the reference signal design used in 5G to obtain the needed channel state information for transmission will not be feasible or efficient.

Furthermore, low-frequency bands are FDD bands, so some of the advancements in channel acquisition for TDD bands, using reciprocity, cannot be directly applied. The realization of distributed Massive MIMO will also dictate a new channel acquisition framework that reduces the feedback overhead and that achieves flexibility to adapt to the deployment and the transmission scheme.

Figure 11 illustrates challenges that will require several research directions to overcome. One challenge that becomes particularly limiting for large-scale MIMO in the low frequency bands is the form factor or antenna size. There is a practical constraint on the number of antenna elements that can be integrated in an antenna array for sub-1 GHz on a traditional rooftop or pole, due to the half-wavelength distance needed between the antenna elements. As such, evaluating new concepts for the integration, modularization, and deployment of antennas will be crucial [42], along with different deployment strategies in a cell-based network deployment, such as multi-panel, multi-Transmission Reception Point (TRP), intra-site and inter-site, or a cell-free Massive MIMO network deployment [43], where a large number of distributed access points (APs) – possibly deployed on irregular non-traditional surfaces or locations – form a distributed Massive MIMO system. The envisioned new antenna modules can have non-uniform, irregular structures and can be flexibly aggregated to realize Massive MIMO gains. Another possible area of consideration is the relaxation of the half-wavelength distance requirement between antenna elements for these antenna panels or modules via compact antenna arrays [44].

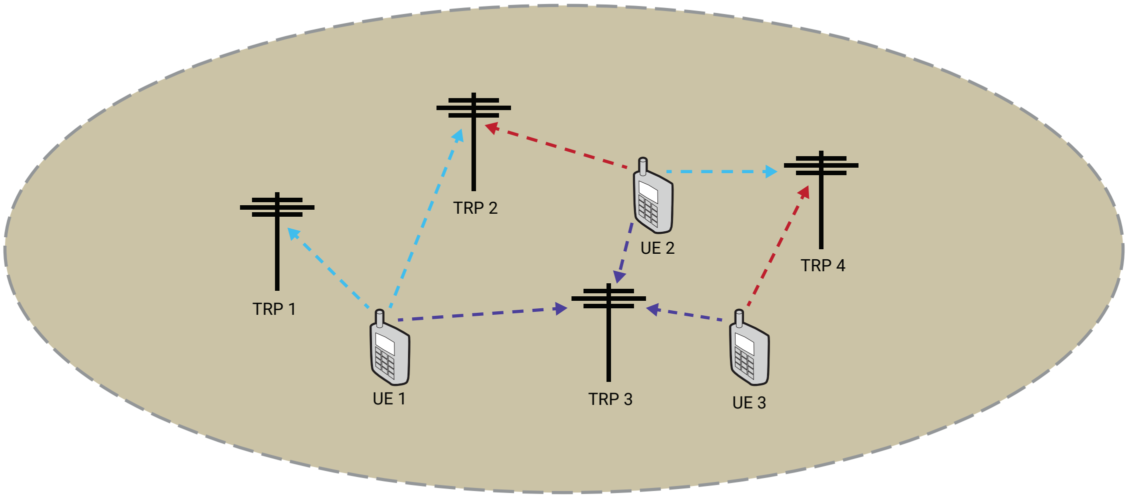


Figure 11 - Example of intra-cell (or cell-free) interference issues encountered for channel state information acquisition

Some of these deployment strategies will inevitably lead to a more distributed means of operation. As a result, the RAN architecture, considering fronthaul and backhaul availability and capacity, needs to be reevaluated. The distribution of functions between the radio units, distributed units, and central units, as currently defined for 5G, needs to be revisited and optimized in terms of maximizing performance and minimizing cost and power consumption.

The distribution of potentially non-uniform antenna panels also leads to more challenges for calibration and synchronization, especially for an FDD spectrum. Synchronization is more challenging for a distributed system where each access point can have an independent oscillator, creating a problem when coherent joint transmission across multiple access points is needed [45].

The potential use of non-uniform antenna panels in addition to a distributed deployment strategy may also create the need for new channel models. This should be investigated and consider factors such as the correlation between elements, and near-field effects and far-field effects of having large antenna arrays and having the users potentially in close proximity to the access points.

Exploring new, efficient reference signal design and acquisition frameworks that have the potential to improve channel state acquisition will be another key area of research for large-scale MIMO in low-FR1 bands. Although full reciprocity might not be possible for operation in FDD bands because the channel is different from one frequency to the other, partial FDD reciprocity can be exploited [46]. The underlying physical paths that constitute the environment between the transmitter and the receiver are relatively similar. By identifying a transform that allows it to map channel parameters at a given frequency to relatively stable (slightly varying) underlying parameters, then map them back to the channel at a different frequency, one can take advantage of reciprocity in FDD systems. This mathematical transformation can be used to feed back channel state information to the transmitter, with less overhead and lower computational burden, resulting in a more efficient reference signal design and channel acquisition.

The potential of AI/ML techniques to aid in tackling the challenges with channel state acquisition should also be evaluated. AI is expected to be natively part of 6G systems and, as such, be an integral part of the channel state acquisition framework. In order to reduce reference signal overhead or mitigate interference, some technologies for channel prediction from one link to another, or from one band to another, may be considered. For example, predicting the DL channel from the UL channel, or vice-versa can be considered as one of future research directions. Channel prediction for low FR1 bands from other bands such as mid bands may also be considered and studied.

3.3.1.3 Conclusion

Low frequency bands will continue to be essential for providing widespread coverage in next-generation cellular networks. Given the limited bandwidth available for these bands and the vital role they play, identifying how technologies like MIMO can be used to improve spectral efficiency is crucial. Massive MIMO as used in the 3.5 GHz 5G bands with 32 or more transceivers is challenging to deploy because the antenna size and half-wavelength spacing requirements limit practical feasibility. A modular or distributed massive MIMO deployment potentially provides a way to overcome these limitations. But it also introduces a range of new challenges, including but not limited to synchronization, calibration, channel state acquisition, and the processing architecture. In line with this, some important areas of research to realize low frequency bands distributed massive MIMO operation for 6G will include considering distribution-aware transmission schemes; new reference signal design and channel acquisition frameworks, including the use of AI/ML techniques; and cross-band channel prediction for FDD.

3.3.2 Advanced Massive MIMO

3.3.2.1 Overview

Advanced massive MIMO technology is expected to be a key enabler of 6G's extremely fast data rates and wide coverage. The primary benefits of massive MIMO can be summed up as:

- Increased network capacity.
- Improved coverage.
- Higher spectral efficiency and data rate.
- Better user experiences.

In addition to the current 5G spectrum — low bands (below 1 GHz), mid bands (1 GHz – 7 GHz), and mmWave bands (24 GHz – 100 GHz) — 6G may expand to upper mid bands (7 GHz – 24 GHz), where a wider bandwidth is available with much lower propagation loss than in higher bands. 6G is also poised to expand into sub-THz bands (100 GHz-300 GHz) where the severe path loss will necessitate high-gain narrow-beams to realize the Tbps ultra-high throughput and sub-ms low latency requirements.

The upper mid bands promise to provide a capacity-coverage trade-off suitable for wide-area deployments and provide new opportunities for 6G new technologies. As shown in Figure 12, the shorter wavelength at upper mid bands supports packing severalfold more antennas within the same aperture size as in sub-7 GHz bands. The additional antennas at both transmitter and receiver end can effectively compensate for the attenuation due to the increased frequency and increase the chances for higher rank transmission in favorable propagation conditions. Together with the availability of GHz of bandwidth, lower phase noise, and higher power amplifier efficiency, advanced massive MIMO at upper mid bands could provide the best of mmWave in terms of data rate and the best of sub-7 GHz in terms of coverage, while enabling high timing/angular resolution for sensing and positioning.

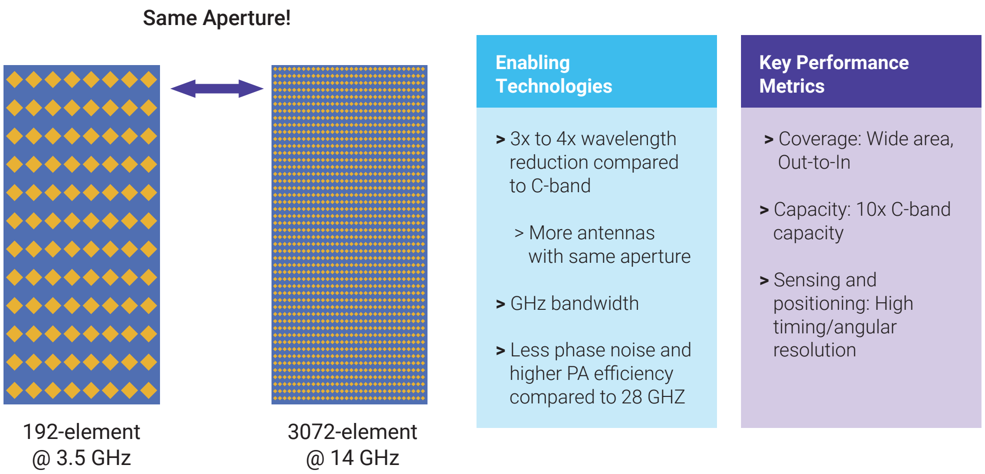


Figure 12 - Upper mid band enabling technologies and key performance metrics

Advanced Massive MIMO for 6G must strive for significant improvements over 5G in the following areas: capacity, coverage, and robustness, including robustness to moderate and high-speed scenarios. With antenna arrays with large numbers of antennas and/or transceivers, the design for 6G massive MIMO will need to put high priority on the performance versus complexity trade-off and on the performance versus energy consumption trade-off. The 6G Massive MIMO design should aim to support "everything and every" scenario including XR and Fixed Wireless Access (FWA) in addition to eMBB and URLLC. With 6G expected to be deployed in the upper mid bands, differentiators will be needed for those deployments, including strategies for co-existence with other deployments in the same band.

3.3.2.2 Challenges and Research Directions

This section discusses several key challenges for advanced massive MIMO implementation across all frequencies considered for 6G.

3.3.2.2.1 Impact of Beam Squinting with Large Channel Bandwidths

Deployments in the sub-THz band (100 GHz-300 GHz) will have two key challenges: (1) high propagation loss requiring high-gain large antenna arrays with pencil-beam characteristics, and (2) wide channel bandwidth. When a large phase array is used with a wide channel bandwidth (a bandwidth greater than, for example, 10% of the carrier frequency), the use of beamforming based on phase shifters causes the direction of maximal array gain to be frequency dependent across the signal bandwidth. This phenomenon is called beam squinting and is due to the frequency-dependent nature of phase shifting. Delay differences across the array are frequency independent, and when the bandwidth is small, phase shifters can approximate those delay differences with reasonable accuracy. However, as the bandwidth increases, a single phase-shift value across the entire signal bandwidth cannot accurately approximate the delay differences, which results in a frequency-dependent direction of maximal array gain.

Mitigating the beam squinting effect involves compensating for the propagation delay differences across the antennas of the array over the total signal bandwidth. True Time Delay (TTD) [47] [48] directly compensates for the delay differences and can be implemented in the RF, analog, and/or digital domains or a combination thereof. Baseband digital architectures can mitigate the beam squinting problem through frequency selective beamforming in the baseband digital domain. The various beam squinting mitigation options have their respective advantages, disadvantages, and limitations. 6G massive MIMO deployments in the sub-THz bands will need to account for this effect.

3.3.2.2.2 Antenna Arrays with Non-Uniform Antenna Spacing

An important consideration for the antenna array design for 6G Massive MIMO is the use of antenna arrays with non-uniform antenna spacing. As an alternative to uniform linear arrays (ULAs), Nonuniform Linear Antenna Arrays (NULA) have non-uniformly distributed antenna elements and, in the process, provide an additional dimension (i.e., the antenna element locations) for optimizing the beamforming and multiplexing gains. Sidelobe reduction, grating lobe reduction, secondary beam suppression, and a comparable beamwidth achieved with fewer antenna elements are some of the improvements that NULAs enable [49]. NULAs promise considerable improvement in array performance in comparison with uniformly spaced arrays having the same number of elements and identical current distribution [50]. Potential use cases may include:

- **Capacity enhancement with interference reduction:** Optimization of antenna spacing to reduce interference and improve overall SNR in ultra-dense network scenarios.
- **Enhanced mobility management:** Improved beam steering range and precise beamforming in, for example, dense urban areas and transportation hubs, where targeted coverage with minimum interference to adjacent users can be provided.
- **Infrastructure deployment cost savings:** Number of antennas and active devices required can be reduced while maintaining the same level of coverage and reducing overall systems cost and power consumption [51], [52], [53].

However, the NULA deployment optimization problem is very complex analytically, and current work on NULAs is based on simulations or brute force exhaustive search [54]. How to systematically optimize the deployment of NULAs for maximizing the multiplexing gain is still an open problem. Potential research directions may include new signaling protocols for CSI and feedback, potentially new precoder matrix designs, and more flexible signaling.

3.3.2.2.3 Techniques for Serving Both Near-Field and Far-Field UEs

For some use cases, 6G is expected to adopt electrically large antenna arrays with up to thousands of radiating elements. To date, wireless communications are mainly studied and designed in the far-field region, where the wavefronts can be well-approximated as planar. For future 6G networks with extremely large antenna arrays, some devices may operate in the radiating near-field region, where the conventional plane wave propagation assumption in far-field is no longer valid and spherical wave propagation needs to be considered. As a result, an important consideration for antenna array design in 6G is the use of techniques for serving both near-field UEs and far-field UEs for Advanced Massive MIMO.

There are several important challenges for serving both near-field UEs and far-field UEs. First, hybrid near-field/far-field channel models are needed to accurately describe the channel characteristics experienced by UEs in the near and far-fields. Near-field wireless channel modeling remains an active area of research. Second, the finite depth of near-field beamforming enables the extremely large antenna array to focus multiple beams in the same direction but at different distances. Near-field Line-of-Sight (LoS) MIMO provides additional spatial degrees of freedom, which can be translated into multiplexing gain. Additional challenges include near-field channel estimation due to complex propagation environment, near-field beam splitting, and so on.

Potential use cases may include multi-user capacity enhancement: Distance-based energy focusing with reduced interference in both angular and distance domain, Distance-based beamforming / precoding, Near-Field Wireless Power Transfer with minimal energy pollution, i.e., radiating energy only at a specific location, near-field integrated communications and sensing, physical-layer security: information concealed from eavesdroppers, enhanced wireless localization and sensing with distance-aware channels exploiting the spherical wavefront. Additional research directions may include adapting the transmission strategy based on whether the UE is in near-field or far-field. AI/ML techniques can be leveraged to improve beamforming and precoding performance over near-field channels due to the complexity and non-linear phase characteristics of spherical waves.

3.3.2.2.4 Beam Management

In 5G NR, the beam management procedures are referred to as P1, P2, and P3. P1 is an initial access type of beam determination, where the base station and UE have no prior knowledge of the best serving beam. In P1, the base station performs beam sweeping over the angular range of interest and transmits SS/Physical Broadcast Channel (PBCH) Blocks Synchronization Signal Broadcasts (SSBs) in each beam. During the P1 procedure, the UE determines a base station transmission (Tx) beam that provides good link quality in terms of Reference Signal Received Power (RSRP) and also selects a proper reception (Rx) beam. P2 is the base station Tx beam refinement procedure, where typically the base station sends out Channel State Information Reference Signal (CSI-RS) in beam sweeping. P3 is aimed at Rx beam refinement for the UE, where the base station transmits the same beam over time and the UE uses the repeated Tx beams to determine the best Rx beam. Although 5G NR defines beam management for both FR1 and FR2, the beam management procedures are primarily leveraged in 5G systems deployed in the FR2/mmWave bands. For 6G systems, beam management-based transmission techniques are expected to be important for consideration in the high FR1 and upper-mid-bands in addition to the mmWave (Section 3.5.2.2) and THz/sub-THz bands (Section 3.4.2.3.1).

Current beam management solutions usually assume an analog beamforming architecture at the base station, and thus also considers single-port beam management Reference Signal (RS). For beam sweeping, typically the beams are selected from a pre-defined analog codebook, where the different beamformers from the codebook point to different directions so that the entire interested range in angular domain can be covered. When there is a large number of antennas, the number of analog beamformers in the codebook becomes large, as well. As a result, the beam sweeping procedure can be very time consuming, especially for large antenna arrays.

In 6G, hybrid beamforming architectures are considered as promising solutions in practice. Figure 13 shows the evolution from conventional analog beamforming to fully digital beamforming. In general, hybrid beamforming capitalizes on the benefits of both digital beamforming/precoding and analog beamforming and can achieve a good trade-off between performance and implementation cost. With hybrid beamforming architectures, beam management can be performed more efficiently, i.e., finding a more suitable beam using shorter time duration. For example, via joint analog beamforming and digital beamforming/precoding, together with the corresponding beam management RS design, the same spherical coverage can be achieved with fewer swept beams over time.

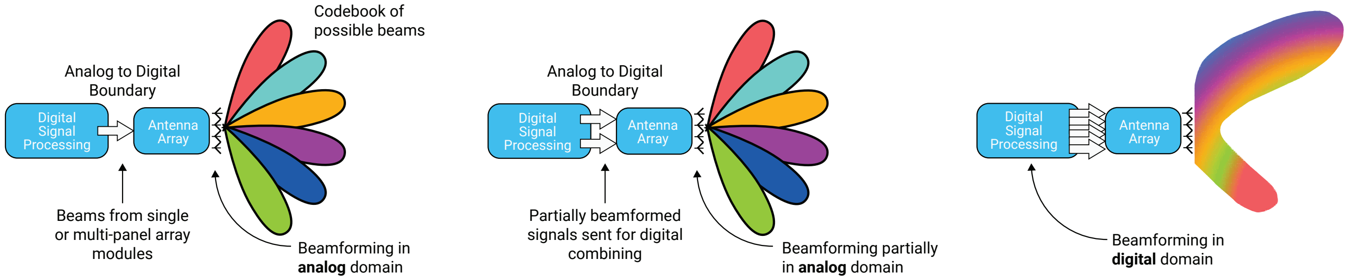


Figure 13 – Illustration of hybrid beamforming

3.3.2.2.5 CSI Acquisition

CSI acquisition is vital to resource allocation, multi-user pairing, link adaptation, and precoding, and hence crucial to MIMO system performance, especially to massive MIMO, distributed/cooperative MIMO, etc. MIMO CSI acquisition faces the following major challenges when applied to massive MIMO:

- Scalability/high overhead of CSI acquisition with extremely large antenna arrays.
- Robustness and overhead of CSI acquisition due to moderate and/or high-speed UE movement.
- Overhead of CSI acquisition due to large amount of reference signal/feedback and interference estimation, at both network and UE.
- Computational complexity at both network and UE.
- Need for scalable and flexible CSI acquisition solutions in time, frequency, and spatial domains while minimizing RS overhead.
- Interference estimation and management, especially in scenarios with highly bursty interference, such as densely deployed MIMO networks with narrow-beam beamforming, adaptive transmissions (e.g., on-demand cell on/off), and fluctuating traffic.

Given the above challenges, we believe CSI acquisition can be improved in the following directions:

- Build upon and extend the scalable CSI acquisition framework defined in 5G NR and move toward reducing reference signal (CSI-RS and SRS)/feedback overhead and increasing flexibility. Multiple measures can be taken, including an increased use of aperiodic CSI acquisition (i.e., transmitted on an on-demand basis), the use of dynamical CSI acquisition (e.g., CSI associated with a data transmission), and an increased reliance on SRS-based CSI acquisition rather than high-overhead CSI feedback. (Techniques for improving the channel estimation from SRS can also be studied.)
- Continue the process started in 5G NR to make the CSI acquisition more robust to higher speed UEs (e.g., the Type II Doppler CSI and AI/ML-based CSI/channel prediction).
- Reduce the complexity and overhead of the CSI acquisition, especially at the UE side, by minimizing the dependence on high-port CSI-RS resources and minimizing the dependency on highly complicated codebook designs. This may be achieved by exploiting the fact that the underlying physical paths that constitute the environment between the transmitter and the receiver are relatively stable in time, frequency, and/or spatial domains.
- Improve interference estimation schemes, especially for bursty interference (e.g., so that interference measurements can better reflect the actual interference conditions experienced in the data transmissions).
- Continue the studies started in 5G NR on applying AI/ML to address CSI acquisition issues. Data-driven AI/ML algorithms can be used to predict CSI based on historical data and promise to improve CSI estimation accuracy and dramatically reduce CSI acquisition overhead.

We believe with these potential enhancements, both the network and the UE can benefit from increased scalability, reduced overhead/interference, and enhanced robustness. In particular, the UE should see reduced complexity for deriving CSI measurements and reports, while the network should have more flexibility in utilizing on-demand CSI acquisition reflecting actual interference conditions (especially for prospective bursty interference) with reduced overhead in RS transmissions and CSI feedback.

3.3.2.3 Conclusion

Advanced Massive MIMO exhibits challenges for implementation across all considered frequencies in 6G. North America has significant capabilities in many key technology areas in 5G in both low band and high band today. To maintain such a strong position in the 6G era, North America needs to keep investing in cutting-edge research to address the main challenges, including beam management to handle mobility with a much narrower beam, much shorter time for beam switching, beam tracking, channel state acquisition, hardware impairments in cost-effective implementation, and energy efficiency/power consumption for very large number of antennas.

3.3.3 Massively Distributed MIMO

3.3.3.1 Overview

Massively Distributed MIMO (MD-MIMO) refers to the systems where a very large number of service antennas located at a large number of locations serve multiple users distributed over a wide area and on the same time-frequency resources. The 5G baseline for multi-TRP operation is non-coherent joint transmission involving two TRPs. For 6G, the goal is to extend that baseline into massively distributed MIMO that is enabled through low-cost densification and scalable methodologies for cooperation and coordination between a very large number of cells or multi-TRPs. Massively distributed MIMO promises to provide system coverage and reliability improvements beyond what is realizable in 5G for operating bands in both sub-6 GHz and mmWave spectrum.

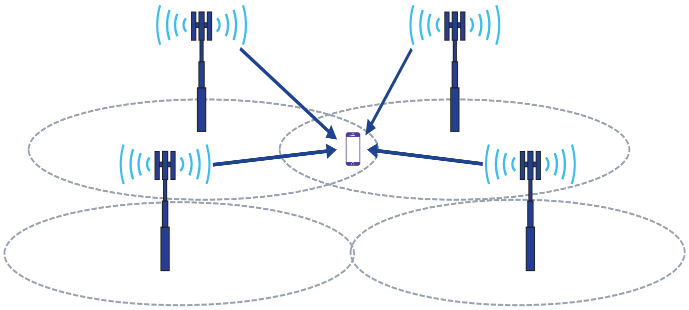


Figure 14 – Massively Distributed MIMO

For massively dense user populations (e.g., dense urban areas), coordinated transmission and interference management promise to provide higher capacities than what can be achieved in current 5G. For mmWave deployments, low-cost densification will be important for mitigating the difficult propagation challenges due to increased path loss, high penetration losses, and high blockage losses. North America currently has significant capabilities in many key technology areas in 5G in sub-6 GHz and high-band applications. To maintain a strong position in the 6G era, North America needs to keep investing in cutting-edge research in massively distributed MIMO to address key opportunities for 6G. Research areas will include:

- Techniques and technologies to enable efficient and low-cost densification, including techniques for lowering fronthaul bandwidth requirements for both symmetric and asymmetric UL and DL densification.
- Enhanced multi-TRP operation enabled by CSI-RS, Sounding Reference Signal (SRS), and/or UL measurements, including advanced pre-coding schemes and schemes requiring synchronization to coherently combine and/or transmit signals from multiple distributed antennas in different locations.
- Enhanced multi-TRP operation for data and control channels and applicable to both DL and UL channels aiming at enhanced reliability and lower latency.
- Enhancements to CSI and SRS frameworks for improved CSI acquisition in massively distributed MIMO, taking into account distributed architecture and feedback overhead.
- Technologies for network infrastructure synchronization and calibration to enable enhanced joint transmission.
- Algorithm design for distributed and scalable signal processing.
- Advanced cooperative techniques including (coherent and non-coherent) joint transmission and interference management (e.g., coordination, cancellation, and suppression).
- Enabling support of high-velocity UEs/High-Speed Trains (HSTs) with massively distributed MIMO.
- Supporting UEs capable of transmitting/receiving higher number of spatial layers (e.g., more antennas and transceivers at low-frequency bands, more transceivers, and panel arrays at high frequency bands).
- An initial access framework to enable efficient on-demand densification via massively distributed MIMO.
- Mobility enhancements to enable seamless mobility in massively distributed MIMO.
- Practical and scalable user-centric (or cell-free) architectures for massively distributed MIMO and advanced massive MIMO [55].

Massively distributed MIMO in 6G will leverage coordinated transmission and interference management techniques to achieve system coverage and reliability improvements for both sub-6 GHz and mmWave bands. MD-MIMO can operate in both DL and UL with massive numbers of TRPs (>> 4 TRPs).

Benefits include coordinated transmission and interference management beneficial with high user densities/traffic levels, as well as lockage mitigation and coverage reliability improvements to enable comprehensive use of all spectrum, including mmWave.

Challenges include: CSI acquisition, coordination schemes, interference management/suppression, mobility enhancements, synchronization schemes for advanced coherent transmission Massively Distributed MIMO.

3.3.3.2 Challenges and Research Directions

3.3.3.2.1 Synchronous and Non-Synchronous Operation

Technologies for Network Infrastructure Synchronization and Calibration to Enable Enhanced Joint Transmission

In a MD-MIMO network, the distributed network nodes may not have the same reference source. As a result, the network infrastructure may experience various impairments, such as time, frequency, and phase misalignments across the distributed nodes. A potential solution for synchronizing and calibrating the network infrastructure is to use bi-directional signaling between a suitable subset of paired distributed network nodes. Using bi-directional signaling, the network captures misalignments at the Tx and Rx sides of each network node. These measurements can be post-processed to estimate and compensate for Tx and Rx misalignments. Devices may also be used as reference nodes (e.g., having device report the reception timing difference in UE-assisted calibration).

Joint phase calibration across distributed nodes in a MD-MIMO network is a major challenge for reciprocity-based coherent joint transmissions [47]. To address this challenge, research can focus on quantifying inter-node phase errors in real deployments, such as determining how accurately the system can be calibrated (e.g., how much phase error is obtained in practice), how long the system remains calibrated, and what factors contribute to phase calibration drifts, etc.

Enhanced Multi-TRP Operation for Non-Synchronous Deployments

In MD-MIMO network deployments, the network nodes may experience time, frequency, and phase misalignments in addition to the fact that UE – TRP distance and UE velocity are different with respect to different TRPs. This is not new. Such imperfections exist in current 4G and 5G deployments. Traditional methods of mitigating such non-idealities include providing per-TRP reference signals that a UE can use for fine synchronization and utilizing joint transmission methods such as non-coherent joint transmission.

In particular, with respect to Rx timing at the UE, the traditional approach limits joint transmission operation to situations where signals arriving from the different TRPs reach a UE within the time duration of a CP (synchronous assumption with respect to Rx timing at the UE). As 5G and 6G MD-MIMO deployments start to utilize high subcarrier spacings and proportionally smaller CPs, allowing for network-side non-ideal synchronicity and unequal propagation distance from a UE to the different network nodes would lead to the non-synchronous multi-TRP operation regime. The main challenge for non-synchronous multi-TRP operation is the resulting un-suppressed cross-TRP interference at the UE.

In a mmWave regime, MD-MIMO operation is desirable and likely because it allows high-rank transmissions and provides improved coverage and resiliency against blockage. In this case, due to the high directivity of panels (digital ports for the panel) at the UE, the resulting cross-TRP interference can be reduced if the best receiving panel for TRP-1 is well isolated from the best receiving panel for TRP-2. Research in this area may focus on methods to dynamically identify such TRP-panel links, achieve DL and UL synchronization toward such TRPs, and provide appropriate CSI feedback reflecting un-suppressed cross-TRP interference.

3.3.3.2.2 Access, Mobility, & Robustness

An Efficient Initial Access Framework (e.g., to Enable Network and UE Energy Efficiency)

Mobile communication systems are traditionally cell-based (i.e., that different TRPs (or sets of TRPs) transmit signals that are tightly associated with different cells). For example, a physical cell identity has traditionally been hard-coded into at least the synchronization signals (as in the 5G SSB), but also in cell-specific reference signals (as in 4G). In cell-based operation, a UE's configuration is associated with its serving cell, and inter-cell handover due to UE mobility may often involve both configuration switching and random access. In a cell-free MIMO approach, the amount of network-cell-based operation is minimized. Instead, UE-centric operation is employed, with seamless mobility and less disruptions due to cell switching. A challenge for cell-free/UE-centric operation is the implementation of dynamic TRP clustering and coordination with non-ideal backhaul between low-complexity TRPs (e.g., distributed and scalable signal processing, CSI acquisition, joint transmission and interference management, etc.).

To enable efficient user-centric cell-free architecture, there are three crucial research directions: initial access, mobility, and clustering. In a UE-centric cell-free MD-MIMO deployment, an efficient initial access framework will be important for ensuring robust mobility and performance. A UE may first be required to determine and connect to a primary TRP before other TRPs can be coordinated to form a cluster [8]. In addition, effective algorithms will need to be employed that allow the primary TRP to assign each UE reference signals in a way that minimizes interference throughout the rest of the network. For a cell-centric MD-MIMO network, initial access will likely not differ greatly from existing massive MIMO networks if distributed operation is only enabled once the UE is in connected mode.

The initial access framework includes synchronization signals, system information acquisition, random access, paging, initial beam management, and mobility, or at least idle mode mobility. The massive number of TRPs are distributed in different directions, at different distances from the UE, and with both synchronous and non-synchronous TRPs. This may require a massive number of distinguishable synchronization signals. Network energy efficiency due to always-on synchronization signals may be challenging. From the UE perspective, a massive number of synchronization signals may negatively impact UE power consumption because more signals need to be received, detected, and tracked. Extensive time-multiplexing of synchronization signals may have a negative impact on UE energy efficiency because it prohibits longer sleep cycles and requires longer measurement gaps. Beside just synchronization signals, the network energy efficiency of other broadcast channels, such as system information and paging, may also be a challenge because they may need to be separately transmitted from the massive number of distributed TRPs.

Mobility Enhancements to Enable Seamless Mobility

MD-MIMO could have the potential to enable seamless mobility and enhance the cell-edge performance experienced in traditional deployments. For example, in a cell-centric system, enhanced soft-handover techniques could leverage the spread of TRPs across each cell to maintain a more consistent connection quality. Cell-free systems could inherently provide this type of enhancement because the TRP or access point cluster dynamically moves with the UE.

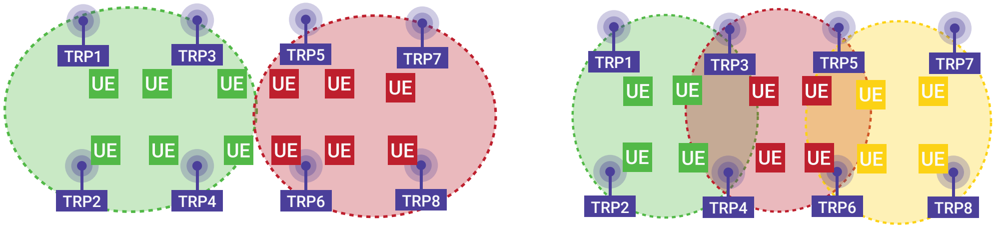
The definition and use of cell should be revisited in 6G, and the corresponding initial access and mobility framework should be redesigned, as well. Clustering refers to the process of identifying the group of TRPs that serve a user. In fact, the goal of MD-MIMO can be achieved only via clustering, where the group of serving TRPs are dynamically selected over time so that the user always experiences being in the cell center. Although clustering is mainly considered as a proprietary operation at the network using available measurements in cell-centric architecture, user-centric architecture may involve over-the-air signalling to configure a group of TPRs for clustering. Research is also needed to address the performance impact of clustering configuration and CSI acquisition delays in user-centric architecture due to mobility.

When considering existing deployments, it is also reasonable to assume that MD-MIMO will likely only be deployed in scenarios where it will provide a gain over single-TRP techniques. As such, the need to simultaneously support single-TRP and MD-MIMO deployments in an effective manner will be essential.

3.3.3.2.3 Scalability & Interference Management

Algorithm Design for Distributed and Scalable Signal Processing. This May Consider User-Centric Architectures/ Clustering

In a deployment with distributed antennas across non-co-located TRPs, clustering and scheduling algorithms need to account for the channel conditions from one or multiple co-scheduled users to multiple TRPs. These algorithms also should be scalable and resource efficient. Depending on the location of each user, only a subset of TRPs may need to participate in joint transmission to serve that user. UE-centric clustering refers to selecting the subset of TRPs per user based on the signal strength, which creates overlapping or non-overlapping clusters across the deployment [56]. On the one hand, this avoids boundary effects as each user can be served by a set of closest TRPs. On the other hand, resolving scheduling conflicts and user pairing for multi-user scheduling becomes a challenging problem. The two cases of cell-centric clustering and UE-centric clustering are illustrated in Figure 15.



Cell-centric clustering

User-centric clustering

Figure 15 – Illustration of cell-centric clustering versus user-centric clustering

Enhancements to CSI-RS and SRS Frameworks for Improved CSI Acquisition Taking into Account Distributed Architecture, Feedback Overhead, and Latency

In a single-TRP massive MIMO transmission, the UE is in a certain angular direction from the TRP. A transmission scheme that directs signal energy towards the UE's direction may work well even if the UE moves to/from the TRP. Some UE movement to a different angle may also result in minor performance degradation, depending on the transmission beam width.

On the other hand, in a massively distributed MIMO system with coherent joint transmission, the communication performance may be more sensitive to inaccurate CSI (e.g., due to small UE movements). Therefore, timely and accurate CSI is essential to achieve the high performance promised by massively distributed MIMO systems using coherent joint transmission.

Furthermore, in a massively distributed MIMO system with non-coherent joint transmission utilizing non-ideal backhaul, instantaneous information exchange of CSI and scheduling decisions within the network infrastructure can be very limited, and tight network coordination may become impractical. Thus, it may be necessary for each TRP to not only acquire CSI information from UEs served by the TRP, but also relevant CSI information from UEs interfered by the TRP (such as via SRS) to prevent performance degradation in the network.

However, when DL-based CSI feedback is preferred (e.g., due to UL coverage limitation), it is preferable that feedback overhead in CSI acquisition does not excessively scale up with the number of network TRPs. Efficient CSI compression for distributed serving antenna and signaling reduction are essential in realizing the benefit of massively distributed MIMO systems.

Techniques and Technologies to Enable Efficient and Low-Cost Densification for Both Symmetric and Asymmetric UL and DL Densification, Including Techniques for Lowering Fronthaul Bandwidth Requirements

In order to facilitate the widespread implementation of massively distributed MIMO technology, transmission nodes must be both easy to deploy and cost effective. This requires consideration of various deployment options in different scenarios because installations must be flexible and scalable enough to support a wide range of frequencies. Furthermore, such networks are expected to offer enhanced interference management capabilities, promoting multi-user MIMO transmissions.

Various challenges have been identified in the fronthaul, including bandwidth requirements, support for multiple frequency bands and antennas, and interference management [2], [3]. Scalable solutions are required to address these challenges and meet transport requirements. To achieve efficient and scalable MD-MIMO networks, lower layer split options must balance processing, complexity, and performance for different topologies, such as star and bus or a combination. Addressing these challenges also involves determining where to perform channel estimation and beamforming, and correspondingly deciding which data should be conveyed through the fronthaul.

Advanced Cooperative Techniques Including (Coherent and Non-Coherent) Joint Transmission and Interference Management (e.g., Coordination, Cancellation, And Suppression) Including the Corresponding Requirements in Terms of Backhaul Latency, Capacity, and Computational Complexity

Joint transmission techniques can be broadly categorized to Coherent Joint Transmission (CJT) and Non-Coherent Joint Transmission (NCJT). Generally, CJT can achieve higher capacity but also requires tight synchronization across the TRPs, low-latency backhaul for data sharing (NCJT may also require low-latency backhaul when the same data or transport block is jointly transmitted across multiple TRPs), and higher computational complexity for multi-user pairing and precoding calculation. Furthermore, CJT allows for interference nulling/avoidance/suppression within co-scheduled users in the same cluster, which requires high-granularity CSI sharing demanding high-capacity backhaul. In the presence of multiple co-scheduled users and/or multiple clusters, both intra-cluster and inter-cluster interference should be properly managed.

For intra-cluster interference, one or both of interference suppression/avoidance/nulling techniques (by precoding at the TRPs) [54] or interference cancelation techniques (soft or hard successive interference cancelation at the user) may be utilized [57]. For inter-cluster interference, more traditional approaches such as coordinated scheduling/beamforming can be utilized, and new inter-cluster interference management approaches may be desirable, especially when intra-cluster interference is significantly reduced, and the inter-cluster interference becomes the performance bottleneck. Moreover, for NCJT, though it is less demanding to the network infrastructure than CJT, it is more challenging to achieve high performance gains due to the infeasibility to exchange scheduling/channel/interference information. Inter-cluster interference management with only non-ideal backhaul needs to be studied. Given these aspects, designing a scalable distributed MIMO system to achieve the desired trade-off between performance, intra/inter-cluster interference, backhaul requirements, and precoder complexity is a challenging problem, which requires further research.

Despite the increase in the number of antennas supported on the network side, there is limited space to incorporate more antennas on the UE side, particularly for smartphone or wearable devices. The MIMO capacity scaling gain of an end user will eventually be limited by the number of antennas equipped by UEs. In addition to joint transmission techniques at the network side, collaborative communication across cluster of devices can be enabled to create a larger virtual array of numerous antennas. Wireless-based techniques for connections among collaborative devices are preferred for user experience and deployments.

5G NR has specified a set of procedures of beam management, which was originally designed for the case of single TRP and then extended to the scenario of two TRPs. For massively distributed TRPs in 6G, beam management becomes challenging because there can be a large number of TRPs concurrently serving a UE, and each TRP needs to find its suitable beam for its transmission toward the UE. In particular, how to achieve efficient beam management is an important research question, especially for higher frequency bands where a TRP can be deployed with a large number of antennas.

3.3.3.3 Conclusion

Massively distributed MIMO exhibits challenges for 6G across all considered spectrum. North America has significant capabilities in many key technology areas in 5G today. The region needs to address the challenges for 6G and keep developing the cutting-edge technologies for research directions, including efficient synchronous and non-synchronous operations, scalability, and interference management, as well as access, mobility, and robustness for MD-MIMO.

3.3.4 Reconfigurable Intelligent Surfaces

3.3.4.1 Introduction

Reconfigurable Intelligent Surfaces (RISs) represent a groundbreaking innovation in radio technologies, enabling the manipulation of radio wave propagation for enhanced wireless communication performance. RISs consist of large, thin meta-surfaces comprising both metallic and dielectric materials, arranged as an array of passive sub-wavelength unit cells. These unit cells can be dynamically controlled through software-defined methods, allowing for the precise tuning of incident RF signals by means of reflection, refraction, focusing, collimation, modulation, or a combination thereof.

Current wireless networks focus on optimizing transceiver endpoints and are limited by the challenges posed by the dynamic multipath propagation environment. RISs, on the other hand, offer new opportunities to improve performance by proactively modifying this environment. As a non-invasive approach that enhances existing RF signals, as shown in Figure 16, RISs hold significant potential for large-scale deployment. However, several challenges must be addressed before RISs can be effectively integrated into wireless networks. Exploring low-cost hardware designs, optimizing the configuration of numerous controllable elements, and demonstrating effectiveness in real-world cellular scenarios are crucial aspects that require further development. Additionally, factors such as deployment and operational costs, ease of site acquisition, and visual impact must be considered to enable large-scale RIS deployments.

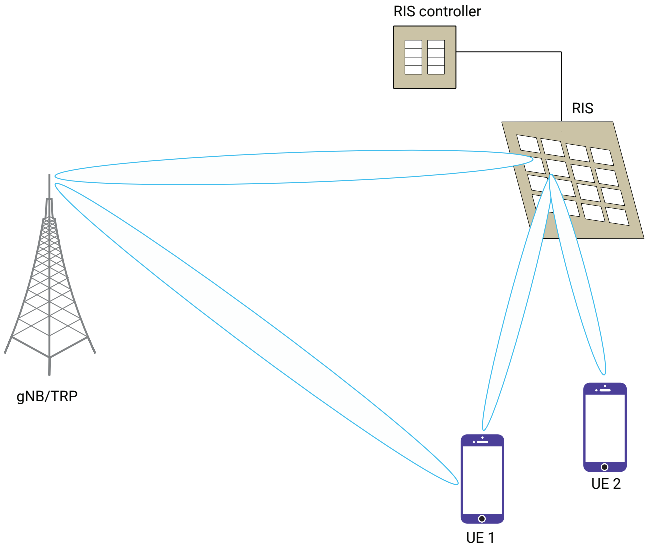


Figure 16 – Non-invasive approach that enhances existing RF signals

As a technology relevant for 6G characterized by software-defined artificial surfaces made of electromagnetic (EM) materials, RISs holds significant promise in revolutionizing the wireless communication landscape. By employing large arrays of inexpensive antennas or metamaterial elements, RISs can customize the propagation of radio waves, leading to significant advancements in the performance and capabilities of future wireless networks. [58] [59].

3.3.4.1.1 Types of RISs

Different RIS types offer diverse functionalities. Most widely studied are Passive Reflecting RISs, referred to here as simply RISs, which enable anomalous reflection of incident signals through controlled phase shifts. These RISs can be further divided into three categories, each with varying degrees of reconfigurability and intelligence, as shown in Figure 17:

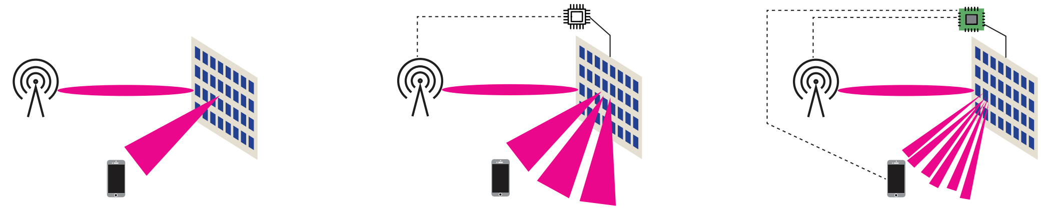
- Type a) pre-configured reflective surfaces, designed for static transmitter and receiver locations, are ideal for patching small coverage holes in indoor and outdoor deployments.

- Type b) partially reconfigurable surfaces offer limited intelligence, enabling networks to choose from pre-configured reflection patterns or beam codebooks, thus extending the network's grid of beams and improving coverage in areas where Type a is insufficient.
- Type c) fully reconfigurable surfaces dynamically adapt to sensed channel information, requiring higher degrees of reconfigurability and an advanced control link to the network. Each of these RIS types presents unique functionalities and use cases, addressing a wide array of wireless communication challenges.

Passive RISs also encompass Refracting RISs that allow signal passage after imparting controllable phase shifts. Researchers are exploring RISs that provide simultaneous and independently controllable reflection and refraction capabilities. Also being investigated are active RISs that incorporate signal amplification through PAs after ensuring sufficient isolation between input and output PA ports. Finally, enhancements to RISs are being pursued to bestow them with advanced capabilities such as sensing, baseband processing, and modulation of incident signals using transmit RF chains.

3.3.4.1.2 Use Cases

Deploying RIS within the wireless network promises to bring new or enhanced capabilities to 6G. The following table and accompanying figures illustrate some key use cases.


(a) Pre-configured reflective surface

(b) Partially reconfigurable reflective surface

(c) Fully reconfigurable reflective surface

Figure 17 – Types of reflective surfaces; from type a to type c, the reflective surface becomes more reconfigurable and more intelligent, while cost and functionality are expected to grow respectively

Table 1 – Example RIS use cases

Use case	Description
Coverage Extension	Mitigate blind spots and impact of blockage (especially for FR2 mmWave) by reflecting or refracting incident RF signals toward coverage holes. Mitigate out-to-in penetration losses by refracting signals to desired spots while preserving signal strength. These use cases are depicted by Figures 18 and 19, upon assuming severe blockage of direct path between TX and RX. Here, TX and RX can be a gNB (TRP) and UE, respectively. It can also be a UE and UE as in sidelink or device-to-device communications scenario.
Enhancing Spectral Efficiency	Enhance system spectral efficiency by improving end-to-end channel rank and/or mitigating (nulling) interference. This use case is also depicted by Figures 16 and 17 upon assuming limited blockage of direct path between TX and RX.
Positioning	RIS can establish a strong reflect path leading to usable measurements with sufficient SNR even in areas without LoS. It can also serve as an additional anchor point to obtain additional positioning measurements with sufficient diversity (variation), resulting in more accurate localization, as depicted in Figure 18.
Integrated Sensing and Communications	Integrating sensing with communications enables leveraging deployed cellular infrastructure and realizing the goal of a perceptive network. Here RIS can remove the necessity of LoS for sensing. In general, by utilizing RIS reflected/refracted signals, a varied set of measurements can be obtained which allows for accurate sensing of target attributes (such as range and velocity). This use-case is depicted in Figure 19.
Wireless Power Transfer	Potentially enhance efficiency of wireless power transfer systems by leveraging beam-focusing capability of RIS.
Vehicle- or Uncrewed Aerial Vehicle (UAV)-mounted RIS	Provide on-demand coverage and assist in disaster management.
Physical Layer Security	Provide physical layer security by selectively blocking signals (e.g., between indoors and outdoors).

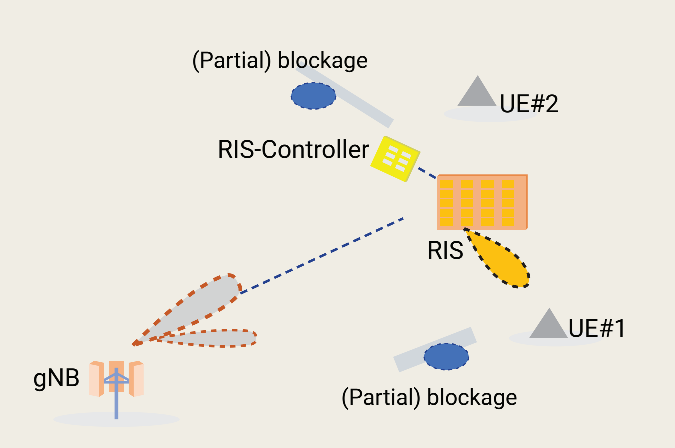


Figure 18 – Coverage or SE refractions improvements enabled by RIS reflections

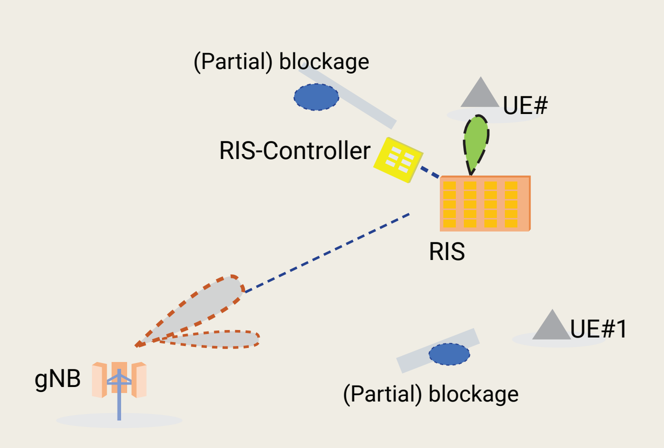


Figure 19 – Coverage or SE gains via RIS

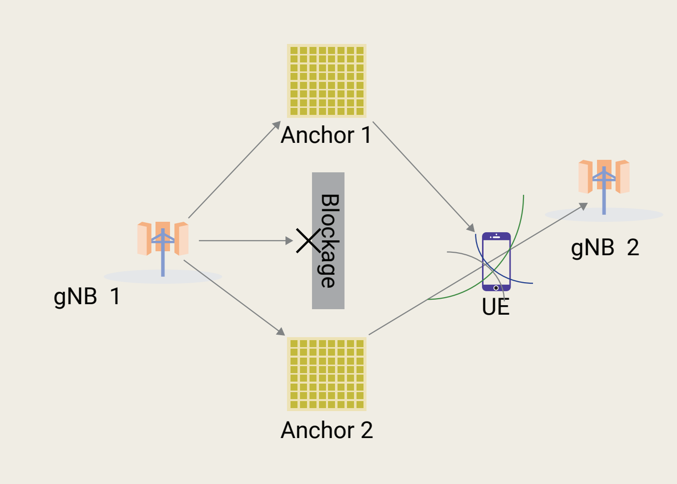


Figure 20 – RIS-aided positioning

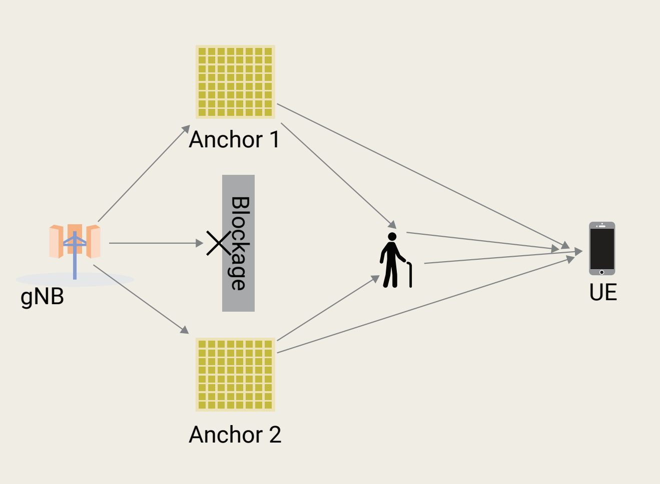


Figure 21 – RIS for sensing

3.3.4.1.3 Materials and design principles

RISs employ materials such as gold, silver, aluminum, and copper for conductive layers, while dielectrics like silicon, silicon dioxide, and polymers serve as substrates. RISs are often built on common printed circuit boards (PCBs) for ease of fabrication. The design principles involve unit cell designs, such as split-ring resonators, tunable elements like PIN and varactor diodes, and phased-array approaches for wavefront control. Advanced optimization and learning algorithms are incorporated to ensure adaptive and energy-efficient performance, making RISs a vital component for next-generation wireless communication systems.

3.3.4.1.4 Comparison with Network Controlled Repeater (NCR)

The traditional approach of relying only on macro-base-stations to operate cellular networks is not well-suited to meet challenges in emerging environments, such as ensuring coverage in dense urban environments. A potential remedy can be densification via full-stack small cells or via IAB nodes. However, these solutions can themselves run into a backhauling bottleneck, as well as energy and cost efficiency issues. Motivated by this, NCR is being standardized in 3GPP beginning from Release 18.

NCR already enjoys key advantages over simple RF repeater which will Amplify-and-Forward (AF) any signal that it receives. Indeed, NCR has the capability to receive and process side control information from the network. This allows it to perform its AF operation in a much more efficient manner, thereby mitigating unnecessary noise amplification, while providing better spatial directivity and simplified network integration. On the other hand, RIS (specifically passive-RIS) represents another alternative relaying node that mainly relies on accurate beamforming capability without active amplification. A conceptual first-order comparison between NCR and RIS is depicted in Figure 22, where components unique to NCR are colored in blue and those unique to RIS are in green. Specifically, NCR allows for pooling of phase-shifted received observations and flexible transmit beamforming post amplification. However, RIS must apply phase compensation (typically from a finite alphabet) on a per-element basis [60] and does not allow aforementioned pooling or flexibility.

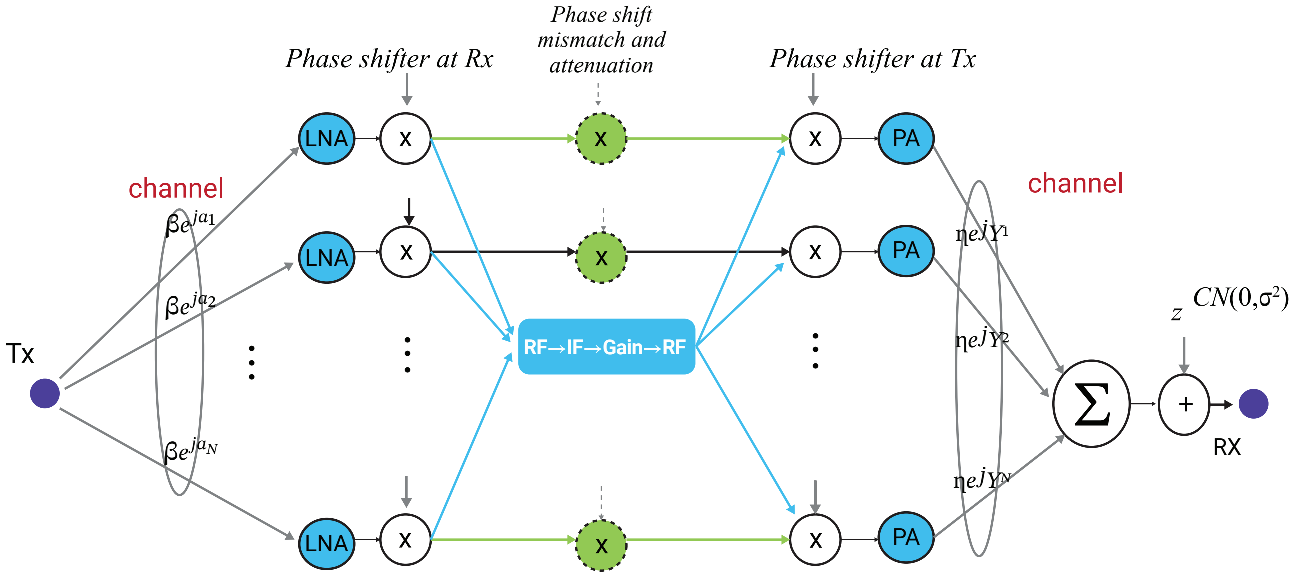
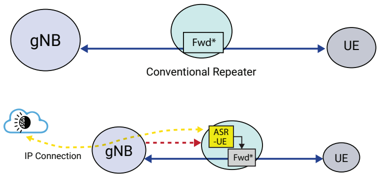


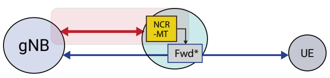
Figure 22 – A conceptual first-order-comparison of NCR and RIS

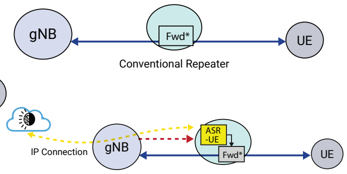
Table 2 quantifies key metrics such as end-to-end gain and consumed power. We note here that NCR also requires isolation between its TX and RX arrays, which sets an upper bound on the permissible NCR gain while maintaining stability. Multiple commercial NCR implementations have indeed addressed this isolation requirement while providing amplification gains exceeding 100 dB. Ensuring isolation, on the other hand, is more challenging in active RISs, whereas passive RIS, being inherently full duplex, has no such requirement. From this first-order comparison, we see that NCR and RIS can be viewed as complementary technologies, and both should be deployed in the right mix to ensure network optimization.

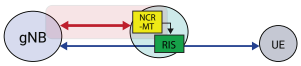
Table 2 – Quantified Key Metrics

	Simple repeater	**NW-controlled repeater**	**Simple reflector**	**NW-controlled RIS**
Power consumption (forward function)	~60W (45dBm EIRP)	~60W (45dBm EIRP)	~10W (Pin diode) or few mW (Varactor) or Zero mW (passive material)	~10W (Pin diode) or few mW (Varactor)
Power consumption for control unit (MT or UE)	Low (cloud-based, UE, e.g., NB-IOT/LTE) or none	~Control channel power consumption of a UE for in-band control	Low (cloud-based, UE, e.g., NB-IOT/LTE) or none	~Control channel power consumption of a UE for in-band control
E2E gain	100+dB	100+dB	~60dB (11cmx11cm size)	~60dB (11cmx11cm size)
Non-linearity of forward function	RF/IF	RF/IF	N/A	N/A









3.3.4.1.5 How RISs Could Enable Advanced MIMO Technologies

RISs hold significant promise for enabling advanced MIMO technologies in next-generation wireless communication systems. By dynamically controlling the propagation of radio waves, RIS can complement MIMO architectures in improving channel capacity, coverage, and energy efficiency. The intelligent reflection, refraction, or modulation of incident signals provided by RIS can enhance the spatial diversity of MIMO systems and facilitate the exploitation of multipath propagation, resulting in a more robust and reliable communication link.

Furthermore, RIS can be employed to create virtual antennas, effectively increasing the number of transmit and receive antenna elements, thereby extending the capabilities of MIMO systems without the need for additional hardware. This approach can be especially beneficial in massive MIMO deployments, where the costs and complexities associated with increasing the number of antennas can be prohibitive. By augmenting MIMO techniques with RIS, wireless networks can achieve significant performance improvements, paving the way for ultra-reliable, low-latency, and high-capacity communication in 6G and beyond [61]. Although RISs add limited gains in terms of ergodic capacity and spectral efficiency on top of more classical beamforming solutions obtained by massive MIMO architectures in static scenarios, they enhance the quality of radio links over time and space, thus reducing the probability that users experience deep fading conditions. When the RISs are deployed in the vicinity of each base station, they can significantly enhance their signal coverage and reduce the associated channel estimation overhead as compared to conventional user-side RISs. This is achieved by exploiting the nearly static ase station-RIS channels over a short distance. In addition, integrating RISs inside the base station antenna radome can significantly reduce the path loss among them and make real-time control of the RIS reflection by the base station easier to implement. This can result in substantial capacity gain over conventional multi-antenna base stations without integrated RIS. With passive RISs, such an improvement does not come at the cost of densifying the network or increasing the transmitting power [62].

3.3.4.2 Technical Challenges and Future Directions

3.3.4.2.1 RIS Design and Fabrication Aspects

Designing and fabricating RIS technologies present several technical challenges and future directions that researchers and engineers need to address. One of the primary challenges lies in the development of low-cost, energy-efficient, and scalable hardware solutions that can maintain high performance in various deployment scenarios. Integration of advanced materials, such as metamaterials, graphene, and liquid crystals, may offer opportunities to enhance RIS properties and functionalities. Furthermore, the optimization of a large number of controllable elements in real-time requires efficient algorithms with low control overhead to cope with the dynamic wireless environment.

Another challenge stems from the deployment and operational aspects of RIS, including site acquisition, low visual impact, and ease of maintenance. Integration of RIS technology into existing infrastructure, such as buildings and urban environments, calls for seamless and non-invasive installation methods, while ensuring robustness against environmental factors such as weather, temperature, and humidity variations.

Future directions for RIS design and fabrication involve exploring novel applications, such as integration with satellite communication systems, IoT networks, and Industry 4.0 use cases. As RIS technologies mature, further research into their role in enhancing security, privacy, and resilience against potential cyber attacks will be crucial. Additionally, interdisciplinary collaboration among material scientists, electronic engineers, and communication experts will be instrumental in addressing these challenges and unlocking the full potential of RIS in the context of 6G and beyond.

3.3.4.2.2 Modeling and Simulation Challenges

Two main approaches for obtaining a consistent model for RIS-aided communications are Infinite Periodic RIS assumption-based modeling and End-to-End Modeling. The former, a more popular method, models the RIS response as the summation of responses of constituent unit-cells, with certain assumptions about RIS control input and array size. Despite these assumptions, this approach has been shown to be accurate over RIS prototypes with sufficient array size and inter-element spacing. The latter approach, on the other hand, relates the excitation currents at the transmitter to the voltages observed at the target receiver but is mainly tractable for simplified scenarios [63].

The main modeling challenges include ensuring accuracy in both near- and far-field regimes over the entire frequency band of interest, incorporating mutual-coupling effects, and developing lightweight models suitable for optimization. Experimental validation of the derived models is also crucial. Moreover, employing realistic benchmarks for performance comparison is vital because inaccurate benchmarks can lead to unrealistic expectations of RIS gain.

System-level simulators are being amended to include RIS functionality by introducing a novel network element in smart radio environments and network planning. Furthermore, improved path-loss models and comprehensive EM characterization of anomalous scatterers, addressing both near-field and far-field scattering, are being developed to accurately estimate the performance of RIS-aided networks via system-level simulations [58], [64], [65], [62], [66], [67], [68].

3.3.4.2.3 Reconfigurability Challenges

For RIS to be an effective and compelling technology, it must ensure low cost and low power consumption. Although significant progress has been made in designing non-reconfigurable surfaces through enhanced printing techniques, there are still challenges in designing mmWave RISs, for which available prototypes or designs are predominantly based on PIN-diodes or EM simulations of varactor-diodes. PIN-diodes can have non-negligible power consumption, while varactor diodes may entail high losses, necessitating further research to overcome these shortcomings. In this context, advanced materials can be utilized to develop energy-efficient phase tuning components [69], [70], [71]. The efficiency of traditional reflect array antennas diminishes for large deflection angles, and losses associated with manufacturing and other practicalities further decrease efficiency. Additionally, extensive designs can be complex to simulate and optimize using full-wave EM simulations, becoming computationally inefficient for electrically large structures. Classical phased array antenna design methodology often ignores mutual couplings and near-field scattering, leading to limited and inaccurate performance in both system-level simulations and practical propagation environments.

To obtain a large SNR gain with RIS, many elements are required leading to high control overhead. Even in the codebook-based approach, due to the high number of combinations of incoming and reflecting signal angles, the control signaling load could be high. To decrease the control overhead, self-controlled [72] and UE-controlled [73] RIS types are proposed. In the former case, RIS senses the environment via power detectors and adjusts its phase shift values accordingly. In the latter case, RIS is like a personal device, and UE controls RIS via dedicated signaling (such as Bluetooth) to maximize its SNR. Although control feedback is reduced in these two alternative approaches, due to the limited knowledge about interference, and other users, performance would be quite limited. As a result, further investigation is required to optimize the trade-off between flexibility in reconfiguration and control signaling overhead.

3.3.4.2.4 Frequency Selectivity Related Challenges

Because RIS is like an analog beamformer without any frequency selective filters, different reflection/refraction beams cannot be formed for different sub-bands. This makes phase shift calculation more complex because users scheduled at different sub-bands should be jointly considered. A beam pattern with many peaks is required to be designed to jointly serve multiple users using sub-bands. Another important challenge is joint initial access and data transmission by RIS. Some OFDM symbols can carry both broadcast (e.g., SSBs) and data symbols (e.g., Physical Downlink Shared Channel (PDSCH) [74]). Due to the wideband operation, RIS cannot design different reflection/refraction patterns for them. This further complicates the design because broadcast beams should be swept in time to search for new users, while data beams are comparably more static. In summary, the RIS reflection/refraction pattern should be carefully adjusted and dynamically changed in time to search for new users without interrupting already existing ones.

With wideband operation, beam squint problems might also occur, especially when the incoming or reflecting/refracting angles are far from the surface boresight. Accurate frequency-selective electromagnetic models are required to analyze the beam squint effect on the performance of RIS.

Another problem related to wideband operation is observed in multi-operator cases. When two different operators use adjacent frequency bands, a RIS used by some of the operators may unintentionally reflect/refract signals coming from the other operator's network. This may result in unpredicted and high interference between two operators' networks. Although there are some ongoing studies on implementing filters in metamaterials [75], a concrete solution has not been identified yet. Further investigation is required to understand the scale of the problem to avoid multi-operator interference.

3.3.4.2.5 Scalability, Integration with Existing Infrastructure, and Deployment

Scalability, integration with existing infrastructure, and deployment considerations are critical factors in the successful application of RIS in modern communication networks. As networks expand, the RIS technology must be scalable to efficiently serve an increasing number of users and devices. It should be designed with the capacity to support more unit cells and sophisticated signal processing capabilities to handle more complex communication tasks. Furthermore, integration with existing infrastructure is vital to ensure a seamless transition and maximize the utilization of current resources [63]. RIS should be compatible with existing hardware and software systems, requiring minimal changes to current network architectures. It should also be adaptable to various wireless communication standards and protocols to facilitate its widespread adoption. Deployment considerations for RIS should consider practical aspects such as physical placement, environmental impact, maintenance requirements, and cost-effectiveness. Ideally, RIS should be deployed in locations that maximize their performance and coverage while minimizing potential disruptions to other parts of the network. As such, careful planning and simulation studies are necessary to determine optimal deployment strategies. Lastly, the economic viability of RIS deployment should be considered, balancing the costs of manufacturing, installation, operation, and maintenance against the benefits of enhanced network performance and capacity [76].

3.3.4.2.6 Security, Privacy, and Resilience in RIS-Assisted Advanced MIMO Systems

RIS technology introduces new challenges and opportunities in these areas, requiring novel approaches to address potential threats and vulnerabilities. In terms of security, RIS-assisted MIMO systems can enhance the robustness of communication links against eavesdropping and jamming attacks by dynamically controlling the propagation environment [68]. However, this also means that malicious actors could exploit RIS to launch attacks on the network, necessitating the development of advanced security mechanisms to safeguard against such threats.

Privacy in RIS-assisted MIMO systems is equally important because the increased granularity of control over the wireless environment may enable more precise user tracking and data profiling. To protect user privacy, the design and operation of RIS should incorporate privacy-preserving mechanisms that minimize the exposure of sensitive information without compromising the efficiency of the system.

Lastly, resilience in RIS-assisted MIMO systems refers to the ability to maintain reliable communication despite the presence of hardware failures, software errors, or external disruptions. This can be achieved by incorporating fault-tolerant designs, implementing self-healing capabilities, and employing robust algorithms that can adapt to changing conditions in real-time. In summary, addressing security, privacy, and resilience concerns in RIS-assisted Advanced MIMO systems is essential to guarantee the safe and dependable operation of next-generation wireless networks.

3.3.4.2.7 Market Potential and Commercial Viability

The market potential and commercial viability of RIS technology are promising because it offers innovative solutions to enhance the performance, efficiency, and flexibility of wireless communication systems. The growing demand for seamless connectivity, driven by the proliferation of IoT devices, smart cities, and Industry 4.0 applications, creates a significant opportunity for RIS to address various challenges related to network capacity, coverage, and energy efficiency. By enabling advanced MIMO systems and intelligent control over the wireless environment, RIS has the potential to optimize network performance while reducing deployment and operational costs. Additionally, RIS can facilitate new business models and use cases in various sectors such as health care, transportation, and entertainment. However, to fully realize the commercial potential of RIS, it is essential to address technical challenges, develop scalable and low-cost solutions, and demonstrate successful integration with existing infrastructure. Ultimately, the market success of RIS technology will be determined by its ability to deliver tangible benefits in real-world deployments, creating value for both network operators and end users.

3.3.4.3 Conclusion

The goal of large-scale RIS deployments is to enable real-time agile control of anomalous reflection in several predefined scattering directions from arbitrary incident angles. This requires characterizing the angular response of the RIS across all possible incident and scattering angles and adjusting it accordingly. Further research could unlock the potential for controlling numerous propagating directions for large, broadband, and multi-bandwidth reconfigurable antennas. Moreover, incorporating RIS into the propagation environment paves the way for new research paradigms in information and communication theory under the concept of a smart radio environment. The channel state can be considered as a degree of freedom for encoding and modulation, which fundamentally differs from classical information theory models that typically treat the environment as transition probabilities. To determine the benefits and challenges of introducing RIS into current communication systems, additional research is necessary to quantify the comparative advantages of deploying RIS versus alternative solutions.

3.4
THz and Sub-THz

3.4.1 Overview

The continuous demand for greater performance from wireless systems pushes the research community to explore larger bands available at higher frequencies. This trend motivates the further exploration, study, and eventual adoption of sub-THz (100 GHz - 300 GHz) and THz (300 GHz - 3 THz) communications as a part of next-generation networking landscape [77], [78], [79], [80], [81]. However, there are several factors and challenges that need to be accounted for in this process.

In particular, to achieve comparable coverage in wireless communication systems, there are two main factors that can limit performance. First, the output power of sub-THz/THz PAs is low and potentially further limited by the signal's PAPR [82]. Secondly, the increased free space path loss at higher frequencies (without considering antenna gains) can lead to reduced coverage [83]. To mitigate these limitations, it is necessary to increase the Effective Isotropic Radiated Power (EIRP) by adjusting transmit power and antenna gain appropriately. This dependency is illustrated in Figure 23, which considers two cases. In Case 1, the EIRP is fixed, and the target transmission data rate is set to 100 Gbit/s. In Case 2, the EIRP is varied to maintain comparable coverage while still achieving a data rate of 100 Gbit/s. Overall, increasing the EIRP can help to improve coverage, but care must be taken to balance the technical limitations of path loss and PA efficiency and the signal processing limitations in terms of, for example, waveform design [84], [85].

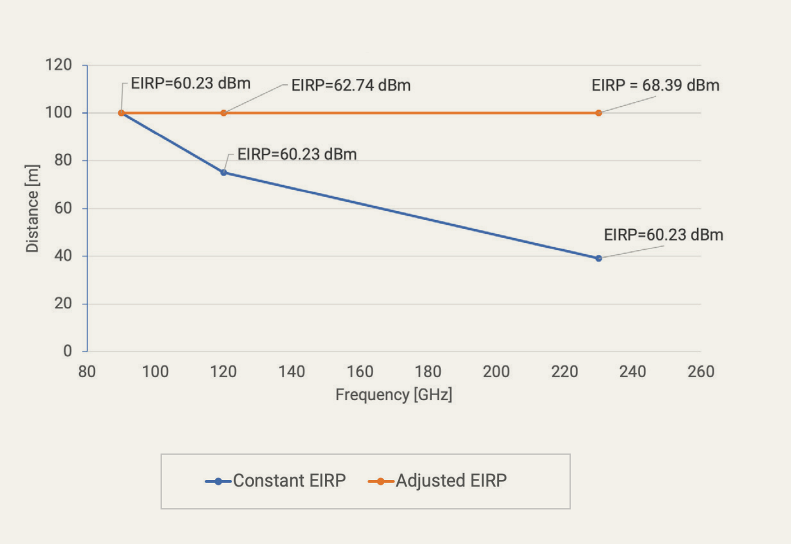


Figure 23 – Achievable distance versus frequency for case 1) fixed EIRP of 60.23 dBm [81] and 2) appropriately increased EIRP where 60.23, 62.74, and 68.39 dBm for 90, 120, and 230 GHz, respectively. (100 Gbit/s, LoS)

When dealing with a fixed EIRP, it is important to assess the required transmit power and feasibility for achieving a certain coverage. In [83], a hotspot scenario with a target data rate of 100 Gbit/s in a 10 GHz bandwidth was considered for bands above 92 GHz. The analysis made some key assumptions, such as a range of up to 100 m, the use of cross-polarization, and two parallel streams per polarization (i.e., 4x4 LoS MIMO). However, wall penetration and reflection at frequencies above 92 GHz are not well-understood, so the analysis focused on LoS scenarios. Despite the challenges, this analysis provides important insights into the power requirements for achieving high data rates in wireless communication systems operating in higher frequency bands.

Table 3 provides link budget calculations for a range of 48 m and two parallel streams with a total data rate of 100 Gbit/s, which only considers transmit array gain, assuming a receive array gain of 0 dBi [84]. These calculations factor in the impact of limited PA output power at higher frequencies, which can be compensated for by increasing the number of transmit chains and resulting in increased array gain. The key finding was that achieving a 48 m range with 100 Gbit/s is possible with a PA output power of 12-15 dBm per array element, provided that the number of PAs and array elements is increased to 120 at 120 GHz and up to 320 at 230 GHz. Such devices are already available in the 90 GHz range, as demonstrated in [86], among other sources. However, the required number of array elements may need to be further increased from 120 (at 120 GHz, with 0 dB back-off) up to 716 (at 230 GHz, with 7 dB back-off) depending on the carrier frequency and back off. By increasing both the total transmit power and the antenna aperture, the achievable range can be extended.

Table 3 – Link budget examples for increasing frequency with fixed data-rate of 100 Gbps

carrier frequency [GHz]	**90**	**120**	**230**	**120**	**230**	**GHz**
no. of parallel streams	2	2	2	2	2	
bandwidth [GHz]	10	10	10	10	10	GHz
target rate [Gbit/s]	100	100	100	100	100	Gb/s
spectral efficiency per stream [bit/s/Hz]	5	5	5	5	5	b/s/Hz
tx output power [dBm]	**18**	**15**	**12**	**15**	**12**	**dBm**
array element gain [dB]	5	5	5	5	5	dBm
number of array elements	**64**	**64**	**64**	**120**	**320**	
array + power gain [dB]	36,12	36,12	36,12	41,58	50,10	dB
total tx EIRP [dBm]	59,12	56,12	36,12	41,58	50,10	dBm
tx EIRP per stream [dBm]	**56,12**	**53,12**	**50,12**	**58,58**	**64,10**	**dBm**
required SNR [lin] (Shannon)	31	31	31	31	31	
Shannon required SNR [dB] (Shannon)	14,91	14,91	14,91	14,91	14,91	dB
Noise power (dBm) in bandwidth	-74	-74	-74	-74	-74	dBm
Noise figure [dB]	10	10	10	10	10	dB
min. Rx signal power [dBm] per stream	-49,09	-49,09	-49,09	-49,09	-49,09	dBm
allowed path loss (LOS)	105,21	102,21	99,21	107,67	113,19	dB
Distance [m]	**48,32**	**25,66**	**9,48**	**48,11**	**47,39**	m

3.4.2 Challenges and Research Directions

There is a need to carefully balance the key numerical parameters determining the system performance (namely, EIRP, frequency, bandwidth, and beamwidth) and the requirement to follow/update the existing spectrum allocation guidelines enabling efficient coexistence of sub-THz and THz communications with other services (both terrestrial and satellite-based). But there are several additional key challenges and research directions, as outlined below.

3.4.2.1 Sub-THz/THz-Enabling Technologies

One of the key challenges in enabling (sub-)THz communications is related to designing the source of the THz signal with sufficient output power and energy efficiency. Currently there are three main research directions explored toward designing the THz hardware: electronic, photonic, and plasmonic, each briefly summarized below.

3.4.2.1.1 Electronic Generation of Sub-THz/THz Carrier Signal

The electronic approach is the most straightforward path toward generating THz and, especially, sub-THz signals. The designs with this approach primarily take the existing solutions from mmWave bands below 100 GHz and aim to extend their frequency to sub-THz and THz bands [82]. Specifically, the most common current technique relies on the use of frequency multipliers (i.e., non-linear devices that can individually double or triple the frequency of the signal at its input and chained to increase higher multiplication factors). This option currently leads to the highest reported output power for THz radios [87] but at the cost of low power efficiency and high phase noise. Digital beamforming arrays at these frequencies have been demonstrated at sub-THz frequencies [88], [89].

Increasing usable bandwidth is as important as increasing the carrier frequency. In this direction, carrier aggregation-type systems are designed to combine several narrower-band mmWave or sub-THz radio chains into a compound sub-THz solution operating two times greater (two units), four times greater (four units), or eight times greater (eight units) bandwidth [90]. The advantages of this approach come directly from its nature: It is relatively simple and mostly backward-compatible with the state-of-the-art architectures and components already adopted for mmWave frequencies (including FR2 and FR2-2). However, the limitations also are present, primarily dealing with the increased power consumption, size, complexity, and costs of the designed hardware. All these aspects, including the aforementioned frequency distortion and phase noise, need to be captured when designing signal processing solutions for (sub-)THz systems [91].

3.4.2.1.2 Photonic Generation of Sub-THz Carrier Signal

In the photonic approach, optical signals are downconverted to sub-THz and THz frequencies. Among the different options [92], the most common strategy nowadays is the use of photomixers to multiply two optical signals with a slightly different wavelength corresponding to the target sub-THz or THz frequency. Currently the photonic approach offers lower transmit power than electronic frequency multipliers, but with the benefit of much lower distortion and phase noise [93].

As mentioned above, generation of clock and Radio Frequencies (RFs) with low phase noise is a challenge at sub-THz/THz frequencies. Integrated photonics employed for generating these frequencies with low phase noise is a research area that can yield dividends. The increased density of antenna elements that will be needed for Massive MIMO is another challenge where research into co-packaging of RFICs, Transimpedance Amplifiers (TIA), Photodetectors (PD), and optical waveguides can help. Optical technologies have been shown to improve beamforming accuracy. Integrated photonic beamformers with enhanced accuracy [94], [95] and photonic frequency synthesizers [96], [97] have also been devised to perform energy-efficient and low-noise signal transmission. Research on integrated optical amplification with low noise, either based on III-V integration or rare earths doping of silicon waveguides, would be beneficial.

Furthermore, advances in the integration of optical, RF, and digital electronics can provide some advantages for operation at sub-THz/THz frequencies. Radio Units (RUs) operating at sub-THz/THz frequencies may need to incorporate more baseband functions than required at lower frequencies due to potential limits on fronthaul capacity that may make it difficult to handle the high data rates supported on the wireless links. RUs capable of sub-THz/THz operation will therefore likely need high-capacity interconnections between digital Integrated Circuits (ICs) and Radio Frequency Integrated Chips (RFICs). The requirements for these optical interconnections will be quite stringent, with a bandwidth density of hundreds of Gbps/mm2, energy efficiency of 1 pJ/bit, latency in nanoseconds, bit error rates less than 10-15, and operation at high temperatures.

3.4.2.1.3 Plasmonic Generation of THz Carrier Signal

On top of the electronic approach (primarily upscaling the frequency to reach the THz range) and optical approach (primarily, downscaling the frequency to reach the THz range), there is also a third approach primarily aiming to generate the source components for the THz range straightaway.

The specific solutions from this category are often referred to as the plasmonic approach and utilize specific nanomaterials (such as graphene or black phosphorus, often combined with III-V semiconductors) to generate, modulate, and detect the THz waves via plasmons [98], [99], [100], [101]. The resulting THz communication devices feature attractive benefits, including a compact design and theoretically lower power consumption. They also may operate over large bands at room temperature. However, the plasmonic approach for THz communications (or THz hardware, in general) is still in its early stages of development, so the timeline for its commercial adoption is anticipated beyond the initial release dates for 6G wireless systems.

3.4.2.2 Channel Modeling above 100 GHz

3.4.2.2.1 Propagation Measurements and Modeling above 100 GHz

Some research activities have been conducted to investigate the characteristics of wireless channels in bands above 92 GHz, including the Path Loss Exponent (PLE), delay and angular spreads (might change as the directivity becomes higher), number of clusters, etc. The measured propagation scenarios can be roughly divided into four categories: outdoor LoS, outdoor non-line-of-sight (NLoS), indoor LoS ,and indoor NLoS. A summary of the research activities can be found in Table 4. The frequency bands of major interests include 140-160, 220-240, and around 300 GHz.

Table 4 – Summary on research activities above 92 GHz; A# refers to the Annex number in [102]

Intended Bands (GHz) Scenario	**[100,120]**	**[140,160]**	**[160,180]**	**[220,240]**	**[260,280]**	**[280,300]**	**>300**
Indoor	A3	A1, A2, A6, A8, A9, A10, A13, A16		A2, A3, A12	A1	A2, A6, A9, A10	A3
Outdoor		A1, A4, A5, A6, A7, A8, A11		A2, A12		A5, A6	

3.4.2.2.2 Propagation in the (Sub-)THz Near Field

One of the essential features of prospective mobile THz communication systems is the fact they may have to often operate in the THz near field [103]. While stationary THz links can utilize physically smaller horn antennas or lenses, mobile systems require beam steering capabilities. Hence, they have to operate with steerable but less efficient antenna arrays and/or intelligent reflecting surfaces. As a result, the near-field zone is naturally increasing [104].

While the exact distances will vary depending on many circumstances, the order of magnitude determined by the Fraunhofer distance (a widely adopted rough approach to separate the near field from the far field) can be as large as several tens or even hundreds of meters for state-of-the-art sizes of cellular antenna arrays scaled to THz frequencies. For example, at a typical Wireless Local-Area Network (WLAN) AP, the antennas can be approximately 10 cm. Keeping a sub-THz access point the same size but using a carrier frequency of 300 GHz, the far-field would start at 20 m. Applying the same logic to cellular-type APs operating at 1 THz with array dimensions up to 25 cm, the far field would begin 400 m away from the transmitter [103], [104].

Therefore, a new research direction recently appeared aiming to explore the challenges and possible solutions of near-field THz band communications. Here, the primary focus is on selecting, generating, and receiving the signal wavefront: the set of all points in the generated EM field having the same phase. Besides conventional far-field beamforming, various other solutions are actively explored, including beam focusing, Bessel beams, Airy beams, etc. [105], [106], [107].

3.4.2.3 THz/Sub-THz Connectivity Algorithms and Protocols

3.4.2.3.1 Beamforming Design Trade-Offs and Comparisons with FR2

Beamforming at the UE side in FR2-1 (24.25-52.6 GHz) relies on the use of a small group of closely spaced (e.g., half wavelength inter-antenna element spacing) antenna elements (typically, four to five) that achieves the array gain needed to compensate the increased path, penetration and blockage losses at these frequencies. Each antenna element cannot be controlled by an independent RF chain due to the increased cost and power reasons. As a result, the antenna elements are often controlled by a smaller number of (typically, a single) RF chains leading to hybrid (or analog) beamforming considerations. The active antenna elements are then integrated with the RF components in a single RFIC. Sometimes, this integrated unit is also called an antenna module. Given the likelihood of the dominant signal at the UE side arriving in any direction over a sphere around the UE (e.g., reflections from vehicles, glass or metallic objects, ground bounces, etc.), and to provide diversity to hand/body blockage, multiple antenna modules are strategically placed within the form factor of the UE.

To maintain a similar link budget at higher carrier frequencies (e.g., FR2-2 corresponding to 52.6-71 GHz and beyond) necessitates the use of more antenna elements within an RFIC. However, the use of a relatively larger number of antenna elements needs to consider the following trade-offs:

1. Architectural considerations that limit the number of antenna feeds that are supported within an RFIC/ Intermediate Frequency Integrated Circuit (IFIC).
2. Power consumption when all the antenna elements are turned on, which also depends on the carrier frequency.
3. Thermal overheads associated with the increased power consumption.
4. Blockage aspects, which can be enhanced at higher frequencies limiting the gains realized in blockage scenarios.
5. Antenna module placement, which is constrained by shared real estate at the UE across different applications (e.g., other antennas, cameras, sensors).

Other aspects that need to be considered in the design of antenna modules at these frequencies include the richness of the channel that determines the number of spatial layers and the type of beamforming codebook design that are relevant (particularly exploring if there are any benefits of upgrading the existing codebook design approaches used in FR1 and FR2 systems), polarization MIMO gains depending on inter-antenna element spacing and carrier frequency, power amplifier technology that can limit the EIRP and the link budget, etc.

3.4.2.3.2 Mobility in THz Wireless Systems

Another important set of research and engineering questions arise in relation to making the prospective (sub-)THz wireless communications mobile. For stationary point-to-point (sub-) THz links, the key challenges lay in designing the efficient hardware and carefully modeling the channel. By comparison, mobile sub-THz and especially THz links demand a careful revisit of connectivity algorithms and protocols used in modern mobile wireless networks [103].

Particularly, the beam steering and beam tracking solutions need to account for the use of even narrower beams. This challenges the link performance and, importantly, reliability, because even a minor displacement/rotation of the UE may cause an immediate outage event [108]. For such a complex setup, several approaches have been recently proposed primarily leveraging additional backup connections (in-band or out-of-band multi-connectivity [109], [110]) certain types of learning-based intelligent techniques adjusting the system behavior to a specific setup at this particular location, this moment of time, traffic, and target KPIs.

A specific group of solutions is related to exploiting the out-of-band channel information, as summarized below.

3.4.2.3.3 Sub-THz Beamforming Assisted by Out-of-Band Channel Information

Beam management for providing mobility support will face severe challenges at sub-THz frequencies. Large pathloss and limited PA output power need to be compensated by a large beamforming gain at both transmitter and receiver. Beamforming gain is inversely proportional to beamwidth, which implies that the optimal beam pair will change often as the wireless device moves in the coverage area of the base station. Sub-THz systems will likely rely on analog beam steering, where only one beam is tested at a time. As a result, frequent updates of the optimal beam pair will result in high signaling overhead and/or large latency due to a large number of beam candidates.

Side information can be used to narrow the beam search to a few beam candidates (e.g., below 10). One example of using side information to narrow down the beam search in the DL – toward a particular UE – is to infer the list of likely beam candidates from an UL channel estimate – from the same UE – performed at another, typically lower, band with a different carrier. Lower bands (e.g., sub-6 GHz) will typically employ fully digital antenna arrays that facilitate spatial channel estimation with high resolution. The features extracted from this spatial channel estimate (e.g., dominant angles of arrival) can be used to infer the most likely DL beams at sub-THz.

3.4.3 Conclusions

While the successful design and integration of (sub-)THz communications into the wireless networking landscape imposes a number of research and engineering challenges, it is almost inevitable to conclude that 6G and beyond wireless systems will (to a certain extent) start exploring (sub-)THz frequency ranges to improve their peak performance.

(Sub-)THz technology can be also a key enabler for other communication technologies, while also benefiting from said technologies such as JCAS. Taking such potential relationships into account may lead to new research gaps to be investigated and highlight areas where one or more of those technologies may be needed to realize new use cases. Such areas include, but are not limited to, channel modelling, waveform and system design with mobility, and beam switching techniques.

3.5
mmWave enhancements

3.5.1 Overview

3GPP Release 15 supports the use of mmWave bands with larger subcarrier spacings and larger channel bandwidths to achieve higher data rates and low-latency transmission. The deployment of mmWave is expanding quite rapidly in parallel with enhancements introduced in Releases 16 and 17 and 5G-Advanced (Release 18+). This includes support for frequency ranges above 52.6 GHz (up to 71 GHz) with new subcarrier spacings (480 kHz and 960 kHz) and up to 2 GHz channel bandwidth. 6G is expected to continue its evolution by targeting improved coverage, robustness, power efficiency, and spectral efficiencies. Enhancements related to beamforming, beam tracking, and topology, including low-cost densification, are key to this evolution.

Lessons learned from existing 5G mmWave real-world deployments and products provide opportunities for potential improvements. 6G can build on top of the existing 5G mmWave technologies while introducing new technologies to enable a cleaner and leaner design. However, the higher frequency ranges for mmWave require continued innovations to overcome certain challenges including, but not limited to, significant path loss due to blockage from obstacles, device form factor related optimizations, satisfying maximum permissible exposure requirements, beam management complexity, cost-effective network densification, and improving power efficiency of network and devices.

North America is in the forefront for adopting 5G NR mmWave technologies, with considerable investments in mmWave spectrum and multiple deployments in macro, outdoor, and indoor environments (e.g., stadiums, airports). Taking advantage of the higher capacity and data rates for mmWave, these deployments enabled multiple new use cases (e.g., Super Bowl stadium coverage). To maintain this North American leadership, 6G research needs to focus on advancing and streamlining the mmWave technology by making it simpler to implement, easier to deploy, easier to integrate, able to better co-exist with current and future technologies, and helping networks and UEs and other nodes have better performance (e.g., better mobility, better power efficiency, improved robustness against phase noise, and better coverage).

3.5.2 Challenges and Research Directions

6G research needs to be aimed at enhancing existing 5G technologies in addition to introducing new technologies to enable more advanced and streamlined systems. Specific research may be focused on enhancements to beam management, coverage, and network-related aspects (including seamless mobility across nodes, and topology enhancements for densifying networks). In addition, UE power efficiency improvements have always been an active and important research area across all mobile technology generations and are expected to continue to be in 6G. On the network side, due to the need for greener networks, energy savings has also become an important research topic for the past few years and is also expected to continue enhancing as part of 6G research. Inter-frequency range and inter-technology operation are also important 6G research topics. An example for this may include multi-frequency range network coding and mobility enhancements across technologies (FR1, FR2, SL, NTN, etc.).

3.5.2.1 Path Losses and Connection Reliability

Although mmWave communications can provide significant gains in data rates, it is sensitive to channel conditions. Compared to lower frequency links, the propagation of high frequency signals suffers from a higher path loss and molecular absorption (such as water vapor), and is more easily blocked by many materials such as foliage, buildings, and even the human body. In addition, unlike lower frequency links — which typically consist of multiple paths and thus the received signal strength is not as sensitive to changes of a single path — the high directivity of mmWave links indicates that the channel mainly depends on fewer paths, and the signal strength fluctuates significantly once these paths are affected, either due to misalignment or blockage. Therefore, although mmWave links can support high data rates, they are also more prone to outages.

mmW's lossy introduces new challenges in MAC and transport layers, such as link quality assessment, rate adaptation, and bufferbloat [111]. Error-control mechanisms at the transport layer can tackle the dramatic path loss but could also lead to blockage-induced timeouts, introducing unnecessary data retransmission (e.g., Transmission Control Protocol (TCP)). Additionally, in order to manage delay, transport protocols commonly use windowing schemes, such as TCP [112], [113]. The use of Enhanced Distributed Channel Access (EDCA) with the in-order block acknowledgment scheme can prevent extra unnecessary retransmissions [114], but at the cost of lowering the MAC goodput (due to holding off the link layer sliding window). The mismatch between current mmWave mechanisms, MAC, and transport layers leads to higher overall delays. These mmWave challenges are particularly salient when we seek to use them for the next-generation Ultra-Reliable and Low-Latency Communications (xURLLC).

Currently, several techniques have been used to correct failures in the wireless channels (e.g., rateless erasure codes [115], [116], systematic codes [117], and sliding window codes [118], [119]).

3.5.2.2 Beam Management

Another direction of research addressing the issue of blockage and propagation losses includes advanced beamforming and tracking techniques used to steer the signal towards the intended receiver, even in the presence of obstacles, known as beam management. As demonstrated in 5G, beam management is critical for good performance of mmWave communication systems [120].

mmWave signals have much shorter wavelengths, so more antenna elements can be packed into a panel compared to lower bands, which can be utilized for beamforming to mitigate the larger propagation loss. In 5G NR, to reduce hardware complexity and cost of the system, analog beamforming with very limited number of digital chains is used, which is also known as hybrid beamforming [121], [122]. The corresponding beam management procedure (e.g., through beam sweeping, beam measurement and reporting, beam indication, and beam failure detection and recovery) is used to obtain and maintain proper beamforming (or beam pairs) between the transmitter and the receiver. As the number of beams grow with narrower beams at higher frequency for a given coverage area, the increased latency, overhead, and power consumption associated with the beam management procedure pose challenges to the efficient operation of mmWave systems.

In 6G, it is expected that services using mmWave frequency bands are to be more demanding compared to 5G. Enhancements are therefore needed to reduce the latency, overhead, and power consumption associated with the beam management procedure. To that end, 6G research may be focused on advanced beamforming architectures beyond hybrid beamforming (e.g., combination of a low-resolution, all-digital panel and an analog/hybrid panel), AI/ML-based beam management methods, beam management enhancements considering potential lack of beam correspondence between DL and UL, and side information assisted beam management enhancements.

There has also been significant progress on beam management since 5G that should be examined for 6G. A comprehensive survey can be found in [123]. In [124], the trends and issues behind six challenges in beam management, as well as recommendations and suggested research directions to address them are provided. Some later works of interest are described below.

Recently, there has been significant progress in using AI/ML techniques to improve beam management that merit consideration for 6G. A survey can be found in [125]. Some very recent advances investigated an UK-means[1]-based clustering and deep reinforcement learning-based resource allocation algorithm (UK-DRL) for radio resource allocation and beam management in 5G mmWave networks [126]. A description of using Q-learning to enhance the mmWave beam handover process was presented in [127]. A mixed regularization training method for training the beam prediction neural network under limited training samples was presented in [128]. A double Q-network under a federated learning framework was proposed in [129]. A grid-free (GF) beam alignment method that directly synthesizes the Tx and Rx beams from the continuous search space using measurements from a few site-specific probing beams that are found via a deep learning pipeline were reported in [130] and [131]. A vision-assisted beam management system concept employed at base stations can select the optimal beam for the target UE, which is based on location information determined by ML algorithms applied to visual data, without requiring channel information [132]. 3GPP is also currently looking at AI/ML for beam management. Recent results using convolutional neural network and a transformer architecture were shown in [133]. An important aspect of the work in 3GPP is the concept of generalization. In real deployments, the system will encounter channels that are statistically different from those that the neural network was trained on. Generalization refers to how well the neural network behaves when it encounters channels that are statistically different from those in its training set. Results will be captured in the Technical Report (TR) [134].

Additionally, using relays can be an interesting solution for avoiding the blockage issues in mmWave. Several recent works investigated joint beam allocation and relay selection using deep reinforcement learning-based approach with terrestrial relays [135] and UAV relays [136].

Although AI/ML holds promising enhancements for 6G beam management, other techniques have also been actively investigated. In [137], a data-driven, multi-armed beam tracking scheme to select the beamforming/combining vectors that achieve the target quality of service based on the real-time measurement was studied. Energy-efficiency constraints were considered in [138] under both short-term and long-term conditions. A MAC and a power allocation/

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[1] Unlike K-means, UK-means compute the expected distance and cluster centroids based on the data uncertainty model.

adaptation mechanism utilizing the Lyapunov stochastic optimization framework and non-cooperative games was presented in [139]. In [140], an adaptive beam codebook management approach was used, where the low-traffic beams are merged, and the high-traffic beams were divided into narrower beams. An ad hoc beam management protocol based on experimental measurements of how received signal strength changes with mobility, beam direction, and on reflected paths was revealed in [141].

What should be clear from the above short survey of the very recent literature is that although mmWave beam management has been a very active area of research, with many techniques that could potentially advance 5G beam management, a holistic technology and strategy for 6G has not yet emerged. Thus much more research is still needed to focus the work onto a comprehensive beam management technique.

3.5.2.3 Network-Related Enhancements

In addition to beam management, network planners must carefully design the network layout and placement of small cells to minimize the effects of blockage and maintain reliable connectivity (e.g., with 95% reliability targets). This leads to the deployment of dense networks to achieve reliable communication. Thus, research will be needed to facilitate denser network deployments, improve coverage, manage mobility, and re-evaluate architectural assumptions.

5G NR has pursued several techniques to facilitate denser network coverage. Release 16 introduced Integrated Access and Backhaul (IAB) to provide a self-backhauling solution through decode and forward allowing networks to easily add additional nodes without the burden of trenching new fiber [141], [142]. Release 17 introduced 5G mmWave repeaters to help plug coverage holes caused by shadowing and improve indoor coverage using a simplified amplify-and-forward solution. Release 18 builds on Release 17 by introducing network control repeaters (a.k.a. “smart” repeaters) that offer the benefit of a simplified amplify-and-forward realization while improving the link budget with beamforming gain managed by the network [143]. 6G will offer new technologies such as RIS that, like smart repeaters, can be used to address coverage holes and be steered intelligently by the network. Further, opportunities for OOB backhaul solutions might be explored by leveraging the abundance of sub-THz spectrum to backhaul access traffic in the mmWave range. All these densification solutions will be the table stakes for 6G. Managing mobility in an integrated network composed of conventional gNBs, IAB nodes, smart repeaters, and RIS devices will require further research to be effective.

New mmWave technologies will pose new architecture challenges for mmWave networks. AI/ML is being studied in Release 18 to aid beam management and improve performance with lower overhead and complexity. Solutions like AI/ML will need to be integrated in the 6G architecture, and the most effective configurations need to be studied [144]. Layer 1 mobility is a new solution introduced in Release 18 allowing a UE to seamlessly monitor beams across multiple transmission points [145]. Architectures to manage the mobility across transmission are an area needing further study.

Additionally, novel coding techniques promising to simplify link adaption, improve reliability, and reduce latency may also allow for greater network centralization. This would reduce the need for adaption at the network edge and allow cellular service providers to better leverage centralized processing to achieve a more efficient cloud RAN. Network coding achieves reliable communication over lossy channels by introducing coded repair packets in a calculated fashion and improves the spectral efficiency compared to retransmissions. It can also combine the windowing to achieve low in-order delivery delay by using Sliding Window Random Linear Network Coding (SWNC), either in a fixed way (F-SWNC) or in an adaptive way (A-SWNC). Recently, an adaptive and causal Random Linear Network Coding (RLNC) scheme was proposed in [146], [147]. The main idea is to track the channel state to adjust the size of the window of packets used to form the RLNC-coded packet in a causal fashion. This feature adaptively tunes the redundancy ratio and error correction capability of the coding solution to obtain the desired delay-throughput trade-off. Recent results show that using A-SWNC in transport layer, mmWave communication can achieve URLLC performance even in the presence of a blockage [148].

On the other hand, an additional avenue of research could be exploring multi-frequency band communication instead of relying solely on mmWave technology. Utilizing network coding techniques would allow for the consideration of multiple communication paths and compensating for signal losses in weaker channels by transmitting additional repair packets over more reliable channels. A possible approach is implementing multipath adaptive and causal network coding, which can dynamically adjust transmission rates over different paths [147] over multiple frequency ranges. For instance, if there is a reliable high-frequency channel, it could be utilized for high-speed data communication. Meanwhile, lower frequency bands could compensate for signal losses caused by mmWave blockages by transmitting additional repair packets whenever a blockage is encountered.
This approach would enable more robust and reliable communication, even in challenging environments where blockages are more likely to occur.

3.5.2.4 Power Efficiency

In addition to the areas discussed above regarding capacity, coverage, and link improvements, power efficiency improvements have always been an active and important research area across all mobile technology generations. In 5G NR, UE power efficiency went through multiple improvements since NR Release 15. In NR Release 16, multiple UE power-saving features were introduced, including (among others) Physical Downlink Control Channel (PDCCH)-based power saving signal (PDCCH-WUS (Wake-Up Signal)), cross-slot scheduling, adaptation of max number of MIMO layers or number of Tx/Rx antenna (panels), dual Discontinuous Reception (DRX) groups, and RRM relaxation in Radio Resource Control (RRC) Idle/Inactive mode. Based on the NR Release 16 power savings study [111], the reported UE power saving gains were:

- 8% - 50% for PDCCH-WUS
- 2% - 28% for cross-slot scheduling

- 3% - 30% for max number of MIMO layers or number of Tx/Rx antenna (panels) adaptation
- Up to 19.7% for RRM relaxation

Further UE power saving enhancements were studied as part of NR Release 17, including paging early indication (PEI) and paging subgroups, providing Tracking Reference Signal (TRS)/CSI-RS occasions available in connected mode to idle/inactive-mode UEs, PDCCH skipping and search space set group (SSSG) switching (5% - 85% power saving gains reported [149]), and UE measurements relaxation for Radio Link Monitoring (RLM) and/or Beam Failure Detection (BFD).

In NR Release 18, additional UE power savings methods are being studied, particularly using a newly defined Low-Power Wake-Up Receiver (LP-WUR) architecture to detect a Low-Power Wake-Up Signal (LP-WUS) [150]. This feature promises a next level for UE power saving gains requiring not only system level and specification changes, but also UE architecture changes. In addition to UE power saving features, NR Release 18 introduced a study to specify Network Energy Savings (NES) where environmental sustainability, reduction of environmental impact (greenhouse gas emissions), and operational cost savings are considered [151].

Enhancements for UE and network power and energy savings will continue as we move into NR Release 19 and beyond leading to 6G.

Additional power savings are very important for both mmWave and lower bands. However, in general, mmWave consumes more power compared to lower bands' operation due to more complexity including bandwidth, RF, and beam management aspects. Based on the NR Release 16 power savings study [149], mmWave consumes up to 75% more power compared to lower bands. This motivates the need to have more innovative methods to reduce the power consumption for mmWave.

Several design aspects for 6G may be considered building on top of existing 5G NR features. Examples include:

- LP-WUR/LP-WUS can be extended to more use cases for mmWave, including eMBB, IoT, XR, and Side Link.
- Beam management (a key component for mmWave) can be designed with power savings as an integral part of its design.
- More power efficient lower PAPR waveforms including single carrier waveforms.
- UE RF-oriented design optimizations may include aspects of antenna/panel switching and management procedures (a 3GPP study showed a reduction of 35% of complexity by going from 2 antenna ports to 1 antenna port [152]).
- gNB antenna/panel switching and management procedures.

3.5.3 Conclusion

6G research needs to be aimed at enhancing existing 5G technologies, in addition to introducing new technologies to enable those more advanced and streamlined systems. Specific research may be focused on coverage and connection reliability, beam management enhancements, network-related enhancements including seamless mobility and topology enhancements for densifying network, power-efficient UEs, and greener, more power-efficient network implementation.

3.6
Joint Communications and Sensing (JCAS)

3.6.1 Overview

Wide bandwidths and large antenna arrays, which are typically associated with high-resolution radar systems, are becoming commonplace in modern communication systems. With 5G and 6G, many key radar bands for high-resolution sensing — for example K (18 GHz-26.5GHz) and Ka (26.5 GHz – 40 GHz) — are close to popular mmWave communication bands. The larger bandwidth of 5G and 6G opens up the opportunities for JCAS. The term JCAS, in 6G context, refers to the introduction of sensing capability as an integrated part of the 6G communication network. This has a variety of use cases: It enables new or enhanced end user services like sensing the presence, movement, and other characteristics of objects under the wireless network coverage. It also enhances the network performance by improved channel awareness. One of the key objectives of JCAS is to share the spectrum more efficiently and maximize reuse of the existing wireless network infrastructure for sensing applications. This is well-aligned with the nature of communication and sensing operations: While the communication theory aims at estimating unknown symbols transmitted over the wireless channel, the radar theory estimates unknown channel-related information by means of known transmitted waveforms. To maximize the coverage area of sensing, the full frequency range from low bands to around 300 GHz is of interest. Figure 24 shows the range of applications for JCAS.

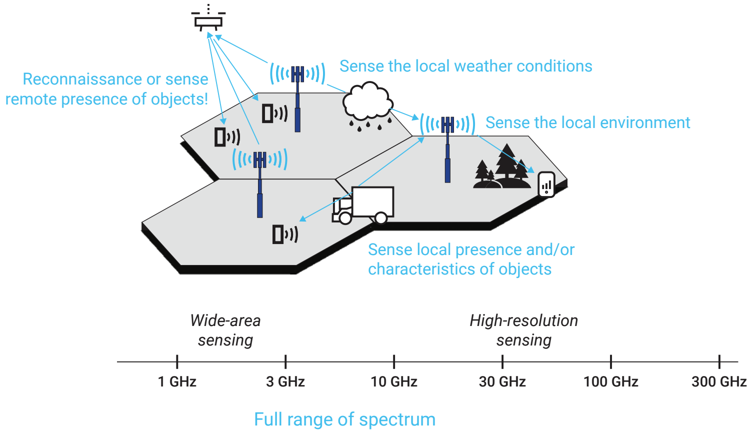


Figure 24 - JCAS enables new services and enhances communication performance by sensing the local environment. The entire range of frequencies can be used for sensing applications

JCAS has received considerable academic interest as part of key technologies envisioned for 6G systems and beyond, see [153], [154], [155], [156], [157], [158]. The 3GPP Service and System Aspects specification group (SA TSG) started a Release 19 study on "Integrated Sensing and Communication" in March 2022 [159]. Some of the envisioned use cases include, among others, detection of intruders inside a home, traffic safety, UAV detection and tracking, and health monitoring. Furthermore, while NGA's Technology WG has identified JCAS as a key 6G technology [160], NGA's Application WG has developed detailed examples of use cases for sensing and the respective approximate requirements in [161]. It is noted that some use cases require sensing processing in order to detect object's presence and estimate its range, speed, and direction. Other use cases, such as environmental monitoring (e.g., weather, pollution), may require processing and inferring from the wireless channel variations. JCAS systems should be designed flexible enough to accommodate wide range of sensing objectives and requirements. It is worth noting that NGA has also started a subgroup to study JCAS channel measurements with National Institute of Science and Technology (NIST) in June 2023 following [162], [163].

While communication and sensing both operate via transmission and reception of signals, distinctions arise in the form of signal design, processing and hardware requirements, and operational aspects. Designing a JCAS system comes with several challenges and trade-offs, as described in Section 3.6.2.1. Channel models for JCAS should provide measures on link quality and assessment of the sensing accuracy to evaluate trade-offs as explored in Section 3.6.2.2. Section 3.6.2.3 discusses radio signal design aspects for JCAS system, while in Section 3.6.2.4, different sensing topologies are discussed. One of the benefits of a symbiotic relationship between the communication and sensing in a JCAS system is enablement of distributed sensing, which can lead to generation of large amounts of sensing data from a plurality of sources. Section 3.6.2.6 touches on the use of AI and ML for processing and sensor fusion. Finally, we deliver concluding statements in Section 3.6.3.

3.6.2 Challenges and Research Directions

3.6.2.1 Key Challenges

Sensing features supported in an integrated sensing and communication framework have to be jointly achievable with the hardware, frequency bands, and the deployment scenarios, which may be largely determined by the communication needs. In a typical sensing application, the sensing detection distance is in the order of tens of meters to hundreds of meters, which means that the backscattered wave should be received within a fraction of a microsecond. In comparison, typical data transmissions use much larger time scales (e.g., in the order of tens of microseconds in a typical 5G OFDM-based air interface). This implies that, in a mono-static scenario (described in Section 3.6.2.4), a communication node should be capable of transmitting and receiving the sensing signal almost instantly (i.e., needs to support full-duplex operation). The challenge of transceiver design with full-duplex capability is well-known because it requires a high level of self-interference cancellation for acceptable sensing accuracy. In bi/multi-static sensing, where the transmitter and receiver are located in different nodes, full-duplex operation is not required. Meanwhile, as will be explained later, other challenges arise, such as synchronization and consistency across the transmit and receive nodes.

The large available bandwidth in the mmWave and sub-THz frequency ranges enable very accurate sensing but suffer from limited coverage and deployments in comparison to wider coverage in lower-frequency spectrum bands. Use of beamforming in high frequency bands to compensate for the propagation loss can also translate into higher overhead due to the sensing and scanning of the environment over multiple beams. These considerations require an adaptive and flexible system design, including the supported frequency bands, sensing numerology, and frame structure, to meet a wide range of system and hardware trade-offs.

Using radio resources for sensing can potentially create interference with communication reception. Given that the radar signal can technically have a simpler regular structure than a (random) communication signal and may also be transmitted with a different power than a communication signal, the intra- and inter-cell interference impacts might be different, and different measures may be required. Further, in a mono-static setup where a sensing node also transmits communication signals in addition to the sensing signal, the increased transmit power, and thus the self-interference to be cancelled, impose additional challenges. Accordingly, monostatic topologies, especially when the network nodes perform sensing, may suffer from self-interference, inter-sector interference, and inter-cell interferences from same operator and others. As such, JCAS systems should support proper measures and techniques to address both co-channel and adjacent channel interference. The distributed (bi and multi-static) sensing (e.g., between the network nodes) may suffer from the similar interference issues as in the monostatic case, except for the in-band self-interference aspect.

Multiplexing of sensing and communication, when and if needed, can pose different challenges in the TDD and FDD domains. For FDD, depending on which nodes do the sensing, a receiver for the other duplex direction might be needed. For example, sensing between the network nodes would require a DL receiver in a base station. Moreover, the UL and DL parts of the spectrum have different requirements in terms of the power level and emissions. In this case, sensing from a communication base station would be allowed only in the DL spectrum, and sensing from UEs would be allowed in the UL direction.

For distributed (bi and multi-static) sensing, there are additional requirements on the nodes' synchronization and consistency in different dimensions: time (to derive the range ellipse), frequency, angle, and phase (to detect the mobility). Due to higher efficiency, it is desired to have the same transmitted signal for illumination of objects and as synchronization reference for accurate time and RF phase synchronization. In this case, a stable LoS/NLoS link is required. Accordingly, the multipath in the reference link must be properly handled. Synchronization across the network nodes may also be achieved through wireline means. On the other hand, synchronization requirements can be even more pronounced when a UE performs sensing operation, which requires additional considerations. Location and sensing orientation accuracy also need to be addressed for multi-static operation.

Another challenge for sensing functionality in cellular deployments is the LoS availability. Almost all sensing applications assume a LoS path between the transmitter (and receiver) and the sensing object, which might be a challenge in most urban environments. When LoS conditions are not sufficiently available for a desired sensing target area (e.g., between an object and sufficient number of sensing transmitter and receiver nodes), measurements obtained with the assistance of intermediate nodes (e.g., RIS, UL-only nodes, or network-controlled repeaters may be utilized for both enhancing coverage and accuracy of the obtained sensing measurements [164]). Model optimization or data inference using AI/ML modules and sensor fusion (e.g., to address some of the challenges) require significant computational resources, which may not be available at the network nodes (i.e., base stations).

3.6.2.2 JCAS Channel Modeling

To evaluate JCAS performance of communications and sensing, spatially consistent and coherent channel models for both communication and sensing are desired. These models should reflect propagation loss and realistic mobility, not only for the user devices but also for the targeting objects. The JCAS channel modeling depends on the sensing measurement topologies, as illustrated in Section 3.6.2.4. Channel model parameters, which can vary across different sensing topologies, should be captured to reflect corresponding sensing measurement topologies. Figure 25 demonstrates the need for different channel characteristics for both target clusters and background clutter clusters with mono-static sensing and bi-static sensing.

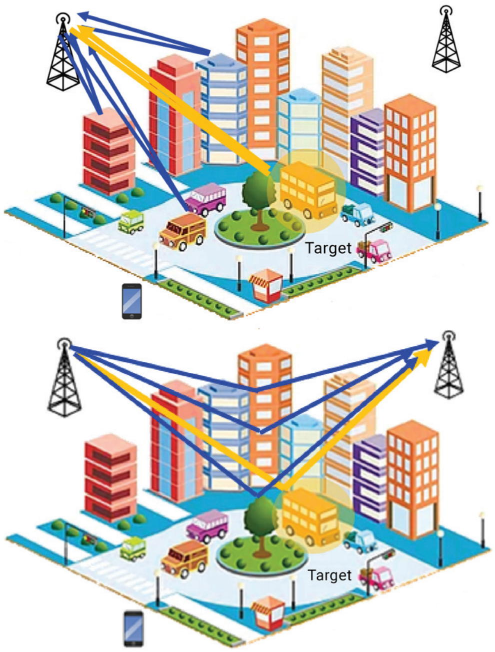


Figure 25 - Channel characteristics for target clusters and clutter clusters vary based on sensing topology. Top: Mono-static topology. Bottom: Bi-static topology

To support forward-compatible analysis with next-generation technologies, the channel model should be valid over a wide variety of evaluation assumptions in terms of target's distance, sounding device height, sensing device height, frequency band of operation, signal bandwidth, target's Radar Cross Section (RCS), and target's mobility.

Unlike channel modeling of communication, a significant factor in target sensing channel modeling is characterization of the reflectivity of the target being sensed, typically characterized as the RCS. Sensing analysis requires accurate representation of the target's RCS over the range of use cases, such as pedestrian, automobile, UAV, etc. Parameterized model of target's RCS can provide flexible integration of sensing targets into the existing channel models. In addition, the channel modeling for JCAS shall characterize channel parameters for the environmental backscatter, including statistics of cluster distribution, cluster angle of arrival/angle of departure/arrival time, etc. Inter-cluster mobility for both target and environment should also be characterized.

JCAS channel modeling with associated parameters should be validated against channel measurement data based on field channel sounding under various indoor/outdoor scenarios over different carrier frequencies (such as 7GHz, 28GHz, and 140GHz). RCS of targeting objects (human, car, drone, etc.) in controlled environments can be measured together with the characterization of the background backscatter. These field-testing data can be used to specify and verify JCAS channel models. In addition to the conventional statistical channel modeling, ray-tracing techniques are important for target characterization and can be applied to validate the channel modeling with a given scenario.

3.6.2.3 JCAS Signal Design

With sensing function becoming an integral part of future networks, JCAS's waveform selection, design, and parametrization, as well as frame structure and resource allocation (in time, frequency and spatial domains), should be dimensioned to operate under a wide range of communication and sensing performance requirements. Such performance requirements may range from high-reliability, high-rate, and/or low-latency communication to high-fidelity (e.g., high resolution, high update rate, and/or high maximum detectable distance or velocity) sensing, as well as hardware and complexity trade-offs. At the same time, JCAS design should enable efficient and flexible in-band multiplexing and resource sharing between the two functions.

The traditional category of multi-carrier waveforms, including the CP-OFDM, can offer several advantages for both communication and sensing, such as high capability to carry communication data with very high performance, as well as good potentials for radar sensing detection, both with acceptable processing complexities. For several use cases, it may be feasible to extend and reuse communication data or reference signals for the purpose of sensing. In some other scenarios, introduction of sensing signal may be inevitable. The possible extent of sharing the resources, and even the radio signals between the communication and sensing, also greatly depends on the transceiver system processing capabilities, as well as the transmit and receive antenna and beamforming architecture. Although in principle, sensing and communication signals may be transmitted via different waveforms, transceiver hardware and signal processing complexities, RF and PA implications, duplexing implementation, and resource efficiency should all be carefully examined to justify the design. For example, the single-carrier waveforms such as DFT-s-OFDM have advantages in terms of low PAPR and PA implications, while they may impose certain limitations in terms of the frequency domain resource allocations. On the other hand, the frequency modulated chirp signals, conventionally used in radar systems, benefit from low-complexity hardware, but have negligible capability to carry communication data and may not allow for efficient resources sharing. OTFS is another candidate waveform for joint communication and radar sensing, which defines signals in the delay-Doppler domain rather than the time-frequency domain as adopted for the conventional OFDM modulation. More details about the 6G waveform design aspects are discussed in Section 3.1.2.

Certain relationships between the fundamental system parameters and the main sensing KPIs (as summarized in Table 5) guide the choice of system parameters to achieve a desired sensing performance. In particular, the sensing signal should be parameterized to meet the requirements for a given use case scenario.

Table 5 – Relationship between system parameters and sensing KPIs (whenever needed, monostatic sensing is assumed)

Design parameter	Relationship to sensing metric	Note
Min required bandwidth	${}^{c_0}/_{(2\Delta d)}$	c is the speed of light, and Δd in the sensing range resolution
Min required sensing frame duration	${}^{c_0}/_{(2\mathrm{f}_c\Delta v)}$	f_c is the carrier radio frequency, and Δv is the sensing speed resolution
Min time domain guard interval between sensing and/or communication symbol allocations	$2d_{max}/_{c_0}$	d_{max} is the maximum inter-symbol interference free detectable range
Min frequency domain size of a sensing allocation	$\gg 4\mathrm{f}_c v_{max}/_{c_0}$ $\approx 20\mathrm{f}_c v_{max}/_{c_0}$	Maximum Doppler frequency, v_{max} , is the maximum inter-carrier interference free detectable speed
Max time domain spacing between sensing allocations (SRI)	${}^{c_0}/_{(4\mathrm{f}_c v_{max,unamb})}$	$v_{max,unamb}$ is the maximum unambiguously detectable speed
Max frequency domain spacing between sensing allocations	${}^{c_0}/_{2d_{max,unamb}}$	$d_{max,unamb}$ is the maximum unambiguously detectable range

As mentioned earlier, although it is fundamentally possible to perform sensing using communication signals (i.e., to share the radio signal between the two functions), this may not be always feasible. For example, the communication signal may not be available in a desired sensing direction, or it may not attain the desired regularity and span over the time and frequency. Accordingly, resource multiplexing between sensing signal and communication data signal may be inevitable and should consider the performance requirements and the compromises concerning both functions. For example, considering the frequency domain dependency of sensing range detection (e.g., increased bandwidths required for better range detection and small spacing between the consequent mapped resources to allow for larger maximum unambiguous detectable range), as well as the antenna architecture implementation requirements, frequency domain multiplexing may not be the proper choice as the baseline operation mode. On the other hand, time domain multiplexing between sensing and communication, provides flexibility to control the sensing transmission and direction independent of the communication, enables flexible waveform selection, parametrization, and use of resources for each function, and can be considered as the baseline mode. For lower frequencies, spatial domain multiplexing can also be part of the baseline operation mode.

It is also worth mentioning that the requirements for range detection resolution and object sensing accuracy for several envisioned sensing use cases may demand transmission bandwidths beyond what cellular systems can offer over a component carrier. Carrier aggregation techniques may be leveraged to increase the coherent sensing measurement bandwidth. At the same time, higher sensing measurement time-bandwidth product may result in range and Doppler migration, which in turn degrades the detection performance if not handled properly. Accordingly, techniques to compensate the range and Doppler migration should be studied for high-resolution sensing use cases.

3.6.2.4 Sensing Topologies

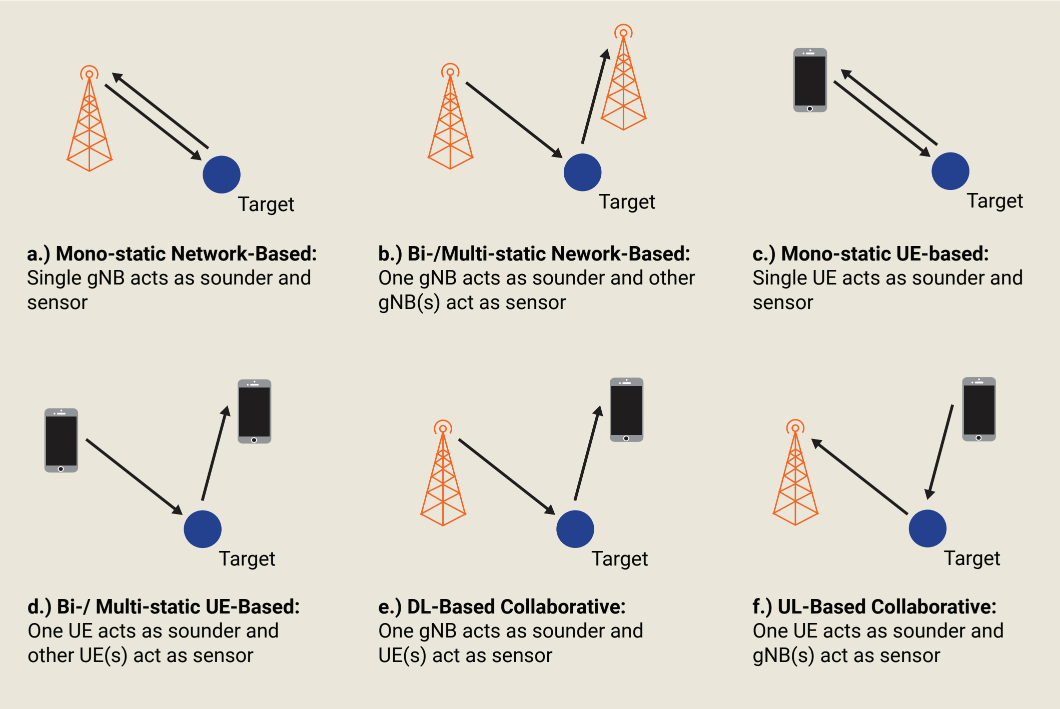
In view of the wide variety of envisioned use cases with diverse KPI requirements and usage scenarios (e.g., indoor, outdoor), different topologies of sensing measurement process can be envisioned, wherein the sensing transmission, sensing reception, and sensing computation/fusion may be implemented in various network and/or UE entities. In this respect, sensing can be mono-static, where the sensing transmission and reception are co-located on the same device (network node or UE), or bi-static, where the transmission and reception entities are separate. For example, one device (network node or UE) acts as a sensing transmitter and another device (network node or UE) acts as a sensing receiver.

The sensing topology can be further grouped into three categories, depending on the UE involvement in the process:

> **Network-based radio sensing:** The sensing measurement process (including sensing transmission, reception and measurements) is performed by one or multiple network nodes.

- **UE-assisted radio sensing:** The sensing measurement process is configured by the network and performed with the assistance of one or multiple UE devices.
- **UE-based radio sensing operation:** The radio sensing measurements are performed without necessary involvement of network nodes for sensing signal transmission and reception.

See Figure 26 for the example sensing topologies. In this regard, the UE involvement in the sensing operation shall be viewed with additional consideration regarding sensing capabilities of different UE categories, synchronization, and resource availability.



a.) Mono-static Network-Based: Single gNB acts as sounder and sensor

b.) Bi-/Multi-static Nework-Based: One gNB acts as sounder and other gNB(s) act as sensor

c.) Mono-static UE-based: Single UE acts as sounder and sensor

d.) Bi-/ Multi-static UE-Based: One UE acts as sounder and other UE(s) act as sensor

e.) DL-Based Collaborative: One gNB acts as sounder and UE(s) act as sensor

f.) UL-Based Collaborative: One UE acts as sounder and gNB(s) act as sensor

Figure 26 - Example topologies of a sensing measurement process, depicting (a) network-based mono-static sensing, (b) bi-static network-based sensing, (c) and (d) UE-based mono-static and bi-static sensing, (e) and (f) UE assisted bi-static sensing.

In addition to the topologies involving base station (active network node) and UEs, the scenarios of UL-only nodes and reflector (e.g., RIS or NCR-assisted sensing measurements) may be utilized to facilitate extended coverage or improved sensing accuracy.

It is worth noting that one or multiple of the above scenarios may be combined to establish a sensing measurement process to support a needed KPI, conditioned on the deployment scenarios and the device/resource availability. Moreover, it can be observed that different topologies of sensing measurement, in combination with a required sensing KPI, will lead to different requirements for time and frequency synchronization of the sensing devices.

3.6.2.5 AI/ML Processing and Sensor Fusion

The incorporation of integrated sensing into communication systems, along with sensor fusion from various sensing systems (for example, LIDAR, cameras, etc.), can unlock the full potential of NextG networks. This enables future networks to cater to a wide array of applications in diverse domains while enhancing overall network performance. By incorporating AI/ML techniques, there is a potential for enhancing data fusion capabilities at the network node and UE device. For instance, AI/ML processing can provide significant benefits in areas such as object detection algorithms and clutter removal by utilizing advanced deep learning techniques with neural networks. Moreover, integrating AI into the air interface of NextG networks opens up opportunities for shared utilization of AI/ML processing for sensing purposes. This convergence has the potential to reduce computational complexity within integrated communication and sensing systems [165].

3.6.3 Conclusion

Integration of sensing capabilities to communication networks can enable new and enhanced existing services and add value to 6G systems. In addition to overcoming hardware challenges related to interference and improving LoS for sensing applications, this integration requires characterization, evaluation, and validation of channel models, careful consideration of signal design depending on the sensing objectives, exploration of various topologies in which sensing can be enabled as well as their respective requirements and limitations, and addressing the role of AI/ML to process sensing data.

3.7
Advanced Duplexing Technology

3.7.1 Overview

5G deployment is based either on paired spectrum using dedicated UL and DL channels separated in frequency (FDD) or on unpaired spectrum using the same channel that is time domain division duplexed (TDD) between UL and DL channels. 5G networks have some capabilities to support the semi-static or dynamic adaptation of the TDD partitioning between UL and DL resources at the base station. However, the extent to which these capabilities can be utilized is limited by the ability to mitigate cross-link and self-interference from neighboring base stations or the same base station, respectively. 6G will enable a new opportunity to go beyond TDD and FDD operation to a new duplexing mode that leverages the benefits of TDD/FDD deployments while enabling higher throughput, reducing latency, and enabling flexible UL/DL scheduling. Supporting advanced duplexing at both the base station and the user device across cellular/sidelink and terrestrial/non-terrestrial communication scenarios can enable 6G networks to leverage the time-, spectral-, and spatial-domain enhancements provided by advanced duplexed operation.

Advanced duplex deployments in 6G should theoretically improve system capacity by increasing UL and DL data rates through simultaneous transmission and reception using same time and frequency resources. In addition, adopting advanced duplexing schemes in new spectrum for 6G (e.g., cmWave and sub-THz) will pave the road to boosting throughput furthermore. Having the UL and DL resources available at any time instance will reduce latency while enabling flexible adaptation to UL and DL traffic demands at both the gNB and the UE.

Figure 27 shows different duplexing modes beginning with a traditional FDD design shown in Figure 27(a). Advanced duplexing that includes non-overlapping UL/DL sub-bands (e.g., Figure 27(b)) can reduce guard bands in FDD spectrum substantially, even potentially to effectively zero. On the other hand, a partially (e.g., Figure 27(c)) or fully (e.g., Figure 27(d)) overlapped UL/DL duplexing presents a full duplex operation. Full duplexing implemented at mid- to high-frequency bands, using spatial and beam isolation techniques, can utilize the larger available bandwidth more efficiently by theoretically increasing spectral efficiency by up to a factor of two in case both DL and UL resources are simultaneously utilized on the same communication link.

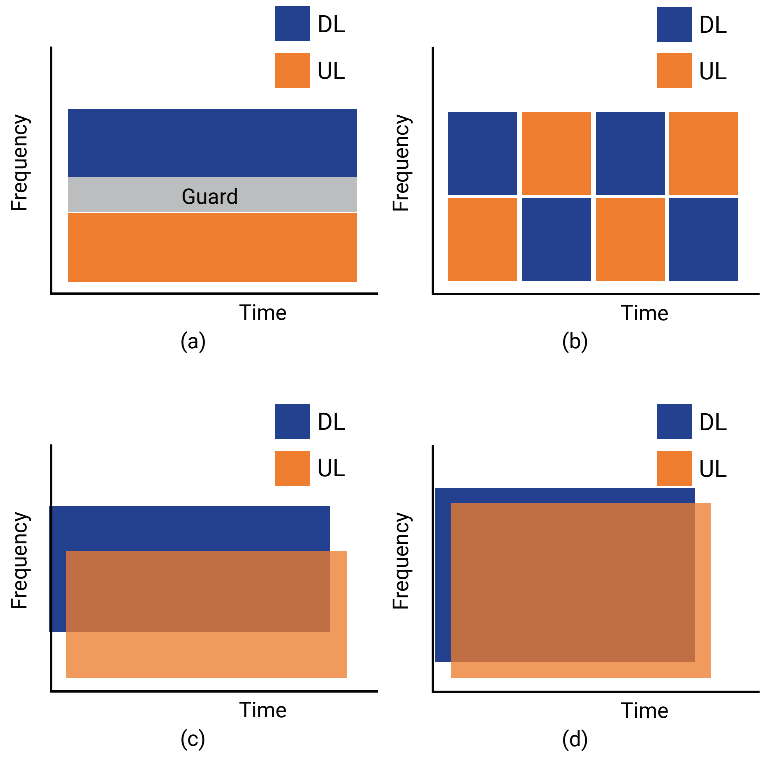


Figure 27 – Different duplexing modes

3.7.2 Challenges and Research Directions

Advanced duplexing may encounter numerous challenges under different deployment scenarios, which include full duplex gNB for macro, micro and small cell, full duplex UE, and full duplex relay, as elaborated below.

The use of adaptive analog/digital beamforming across one or multiple antenna panels can increase the feasibility and performance of full-duplex operation in higher frequency bands thanks to improved spatial and beam isolation. One critical issue across all scenarios is the need for cross-link and self-interference characterization, handling, and mitigation. The extent of the challenges and potential solutions may differ based on transmit power (e.g., macro or micro base stations), device form factor (e.g., handheld UE, Customer Premises Equipment (CPE), UAV, satellites, etc.), number of Tx/Rx chains for interference cancellation, and the use of overlapping versus non-overlapping UL/DL transmissions as some examples. Furthermore, full-duplex scheduling algorithms must counter the challenges of inter-device in-band cross-interference in dense and/or mobile UE environments. Additionally, the need for interference mitigation may extend beyond a single 6G deployment but could also extend to co-channel or adjacent channel deployments belonging to different operators and may further include legacy device impact considerations.

Self-interference cancellation is a fundamental challenge at the transceiver to extract meaningful data from the received signal. Choosing a suitable self-interference cancellation scheme depends on scenario-specific requirements, such as feasibility of start-up tuning or coherence time and bandwidth of the communication channel. In most cases, practical self-interference cancellation implementation is unlikely to reduce the interference level down to the noise floor or low enough to avoid receiver desensitization. Operating with such non-ideal self- and cross-link interference cancellation with potentially degraded signal-to-interference-plus-noise ratio is a challenge that needs to be addressed. Non-linearity of transceiver hardware introduces additional challenges. Cost-effective implementation of non-linear cancellation is a further challenge to be addressed for widespread adoption of advanced duplexed technologies.

Managing system-level interference, such as cross-link interference among network nodes is a further challenge. This includes co-channel and adjacent channel cross-link interference among UEs operating with overlapped or non-overlapped bands and between base stations of the same operators, as well as those belonging to different operators. Multi-carrier operation, as well as inter-sector interference, especially between different operators, also present significant challenges that must be addressed. Further impacts to legacy UEs that are not designed to coexist with advanced duplexed deployments in co-channel and/or adjacent channels is a challenge that needs to be addressed. Finally, it is important to address the challenges listed above taking into account power efficiency and sustainability considerations.

3.7.2.1 Research Directions

From a North American technology leadership perspective, there are multiple research areas that are key to ensuring that advanced duplexing schemes such as full-duplex operation can be practically applied to 6G use cases and deployment scenarios for enhanced digital world experiences. These include defining channel models for the near-field of the Tx/Rx panels and performance evaluation methodologies for various interference scenarios and frequency bands which take into account the impact of both near-field and far-field (e.g., reflections) effects as shown in Figure 28.

Another area is the development of technology enablers including:

- Advancements in RF, analog, antenna, and interconnect hardware to improve spatial and frequency domain isolation and interference suppression.
- Development of self- and cross-link interference estimation, cancellation, and interference avoidance/mitigation techniques enabled by the air interface.
- Development of techniques to mitigate the impact of transceiver non-idealities.
- Additionally, advanced duplexing schemes should be considered in the protocol layer and network architecture design to natively leverage the capabilities on a link and system basis.

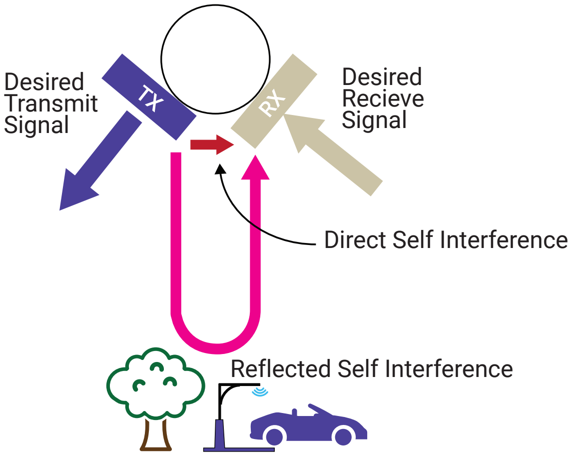


Figure 28 – An illustration of different interference sources in advanced duplexing

The following are some of the research areas that are key to study advanced duplex technology and to ensure that advanced duplex techniques are ready for 6G use cases and deployment scenarios.

Challenges in implementing each of the three forms of frequency band overlaps in advanced duplexing — namely non-overlapped and/or dynamic TDD, partially overlapped, and fully overlapped full-duplex operation — need to be individually addressed. Furthermore, duplexing solutions depend on band-specific requirements. For example, beam-based isolation may be more suitable for higher frequency ranges (e.g., mmWave, sub-THz), while other forms of passive suppression techniques, like antenna separation. May be more appealing at lower frequencies. System-level deployment considerations, such as full-duplex base station for macro, micro, and/or small cell deployments, also drive the type of research problems to be considered for advanced duplexing.

Apart from full-duplex enabled UEs and base stations being able to theoretically double their UL and DL throughputs, full duplex opens a wide range of alternative deployment scenarios. A full-duplex-enabled relay could double its forwarding efficiency. For example, an NTN platform operating in a transparent payload fashion can support a simultaneous in-band service- and feeder-link operation. This could potentially reduce the end-to-end latency that is a significant loss factor for NTNs. Other relaying scenarios, such as integrated access and backhaul or sidelink relays, can also substantially benefit from a full-duplex-enabled relay node. A convenient benefit of full-duplex relays is that the complexity of self-interference cancellation can be confined to the relay node(s) and not the end user devices, which could be low-power, low-complexity devices operating in a traditional duplex manner.

Full duplexing also allows nodes to autonomously access shared channels (e.g., unlicensed bands, dynamic spectrum shared bands) with simultaneous transmission and spectrum sensing. Traditional listen-before-talk methods can be replaced with more efficient listen-and-talk solutions whereby nodes can cancel their own transmissions to determine continued availability of the operating band. Carrying listen-and-talk solutions in its arsenal increases the applicability of 6G as it ventures into previously unused bands.

To design or choose self- and cross-interference-cancellation methodologies, it is important to consider modeling of the various interference scenarios. For example, self-interference in the wireless node and cross-link interference between nodes in the same network may be reduced or avoided based on known signal training. Cross-link interference between nodes belonging to different networks needs to be addressed, specifically in dense deployments. It is also critical to develop models for diverse interference scenarios for technology evaluation.

Technology enablers for advanced duplexing at a wireless node and across nodes in the network include RF-domain, analog, antenna and interconnect hardware, spatial and frequency domain isolation, and interference suppression. Self-interference cancellation can be achieved in various configurations. Analog cancellation may be suitable for countering non-linear hardware impacts, whereas digital cancellation may be efficient for low-cost adaptive self-interference cancellation. Similarly, passive isolation and avoidance techniques, such as efficient beam management or antenna isolation may provide a first line of defense, due to the ability to steer Tx/Rx beams away from directions that result in strong interference, while estimation and cancellation at the back end might be an inevitable fallback. Much of the research toward the design and implementation of self-interference-cancellation methods will be driven by the deployment scenario constraints and hardware flexibility available. Further research is needed into self- and cross-interference estimation and cancellation techniques, including analog, digital, and hybrid domain versions, time-, frequency-, and mixed-domain solutions, interference-avoidance techniques, and methods to mitigate impact of transceiver non-idealities on advanced duplexing schemes.

Transition to a “fully” full-duplexed system needs to be gradual. It is important to consider scenarios where full-duplexed nodes coexist with legacy and/or differently duplexed nodes (e.g., UEs supporting sub-band non-overlapped duplexing, UEs supporting partial overlap, UEs supporting flexible TDD, etc.) for co-channel and adjacent channel interference management, which may depend on the spectrum used (e.g., partially overlapping FDD versus full-duplex operation).

3.7.3 Conclusion

The introduction of 6G RANs presents a new opportunity to go beyond TDD and FDD operation modes, via full-duplex operation that leverages the benefits of both TDD and FDD deployments and is supported at both the base station and the user device across cellular/sidelink, and terrestrial/non-terrestrial networks communication scenarios. In addition to operating in the frequency ranges currently supported by 5G networks, adopting full-duplexing schemes in new spectrum for 6G in even higher frequency ranges (e.g., upper-mmW/sub-THz) can boost system performance and facilitate key 6G use cases such as ultra-precise localization and sensing.

3.8
Holographic Beamforming and Orbital Angular Momentum

3.8.1 Holographic Beamforming

3.8.1.1 Overview

Ultra-massive MIMO is considered one of the key enablers for the high data rates and spectral efficiency envisioned in 6G. The conventional way of realizing ultra-massive MIMO (large-scale phased antenna arrays) can be challenging due to high power consumption and manufacturing cost originating from the numerous PAs and phase shifters. To overcome these, Reconfigurable Holographic Surface (RHS) using holographic beamforming [166], [167], [168], [169], [170], [171] has been proposed as an alternative to achieve ultra-massive MIMO.

Holographic beamforming is a new beamforming technique that leverages optical holography principles with intelligently steered antennas to transform reference waves into the desired beam shape and direction [172]. It uses a fully configurable metasurface that provides lower cost, size, and power architecture over conventional hybrid beamforming architectures. RHS is composed of many metamaterial elements (or meta-elements) packed closely together. An example of RHS transmission mode is shown in Figure 29, where the RHS mainly consists of three parts:

- **Feed:** embedded in the bottom layer of RHS to generate reference waves, propagating along the RHS and exciting the electromagnetic field of RHS.
- **Waveguide:** propagation medium of reference wave.
- **Metamaterial radiation elements:** Each element’s electromagnetic response is controlled such that the radiation characteristic of waveguide reference waves dictated by the electromagnetic response of each radiation element. Elements can be selected to transmit or not by detuning them out of band by a switchable circuit.

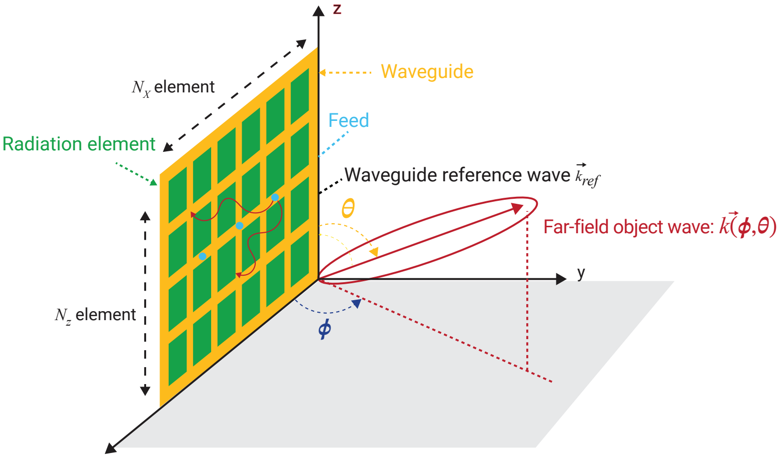


Figure 29 – RHS illustration

RHS is a special leaky-wave antenna [166]. The excitation propagates from the feed across the aperture of RHS towards the edges and excites RHS radiation elements sequentially. Radiating elements (metamaterial elements) leak a part of the propagating wave into free space and achieve a radiation pattern.

There are in general two steps of configuring RHS: (1) Calculate the electric field (amplitude and phase) on the aperture of the RHS that will generate a desired radiation pattern; (2) compare the phase of the reference electric field propagating in the waveguide with that of the electric field on the aperture (calculated in step 1) and control amplitudes of the RHS radiation elements as a function of the phase differences. Elements whose reference waves are in phase with the objective wave are tuned to radiate strongly (large radiation amplitude responses), while the out-of-phase elements to be detuned (small radiation amplitude responses) [8], all while satisfying spatial sampling requirements. This is the basis of holographic beamforming, which uses optical holography principles with passively steered antennas to transform reference waves into the desired shape and direction [172].

3.8.1.2 Challenges and Research Directions

Holographic beamforming using RHS is a relatively new research area in the domain of wireless communications. RHS with holographic beamforming is distinct from classical phased arrays because they do not use discrete phase shifters to accomplish beam steering by the antenna. A number of promising research areas are identified here, in order to bring holographic beamforming into reality with 6G communications:

- **Beamforming control algorithms:** Unlike existing phased array antennas that use phase shifters at each radiating element, holographic beamforming manipulates the amplitude and phase of the signal at each radiating element through a coupled feed line [173]. Therefore, existing phase shifter implementations for 5G cannot be reused. New algorithms need to be studied for beam steering. In addition to maximizing the array gain towards the target direction, the sidelobe cancellation techniques should also be considered.
- **Hybrid holographic beamforming:** RHS itself doesn't have any digital processing capability, so the associated transmitter/receiver needs to process the signal at the base band. One way is to connect each RF chain to a feed (i.e., the number of RF chains is the same as the number of feeds). This is referred to as hybrid holographic beamforming. In this case, the digital precoder and holographic beamformer can be jointly optimized. Performance comparisons to conventional hybrid beamforming may also be of interest.
- **Serial feeding:** RHS utilizes the method of series feeding across the elements. Most existing work assumes a lossless plane wave for the reference wave. However, in a practical waveguide, there is signal loss effect in reference wave propagation. The RHS size must account for trade-offs in a way where signal propagation loss effects are managed.
- **Channel acquisition:** The number of RHS radiation elements can be large, so the corresponding overhead required for channel acquisition will be overwhelming because of RS and channel state information feedback. In this case, the efficient channel acquisition mechanism is a crucial design aspect (e.g., channel sparsity may be utilized to reduce RS overhead).
- **Hardware implementation:** The main design aspects are element spacing and fabrication methodology. The key focus of fabrication is the metamaterial radiation element with controllable radiation amplitude, which has different options including PIN diode, varactor diode, and liquid crystal [166].

3.8.1.3 Conclusion

RHS using holographic beamforming is considered an efficient way to realize ultra-massive MIMO, especially for large antenna arrays. Following the holographic interference principle, the amplitude-controlled method of holographic beamforming can effectively steer the beam toward the desired direction. Holographic beamforming is a relatively new area in wireless communication and has several directions yet to be researched. [174]

3.8.2 Orbital Angular Momentum

3.8.2.1 Overview

OAM of EM waves has been known since the 1990s in the field of optics and physics [175]. Since the discovery that light beams with helical phase fronts can carry OAM, subsequent research has further explored how OAM can be applied more broadly to RF transmissions [176]. As far as wireless applications are concerned, there have been experiments with high-speed transmission in the 17 GHz and 80 GHz bands demonstrating that OAM multiplexing can achieve large capacity in the mmWave bands [177].

OAM is an EM wave property that describes the helical phase pattern of a wavefront. In short, OAM tells us the degree of "twist" of a beam. The amount of phase front "twisting" indicates the OAM mode, and beams with different OAM modes are spatially orthogonal. OAM relies on the creation of many orthogonal modes that can be used to improve the spectral efficiency. Existing multiplexing techniques for communications have included time, frequency, amplitude, phase, polarization, and spatial diversity. OAM brings potential for another degree of freedom beyond these traditional techniques.

The main Interest of OAM is the possibility to preserve the orthogonality between multiplexed layers. In practice, these gains are achievable for short hops under ideal LoS propagation and antenna alignment conditions. Because of these constraints, the targeted applications are fixed point-to-point transmissions, typically backhaul or fronthaul.

Spiral Phase Plate (SPP) antenna and Uniform Circular Arrays (UCA) or Metasurface are considered to create the OAM vortex [177]. Only UCA is capable of supporting modes multiplexing on the same antenna and is briefly described below.

Figure 30 represents the basic OAM concept for UCAs:

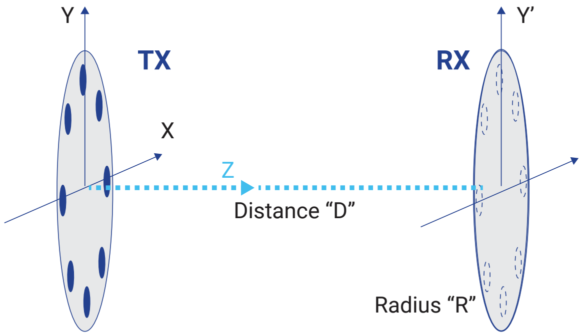


Figure 30 – OAM basic principle (eight antennas case)

N antennas are arranged along a circle at equal angles on the transmitter and receiver sides. Omni or directional antennas are possible. The precoding principle consists in applying a progressively increasing phase rotation: Mode m is obtained by applying a counterclockwise rotation of on the nth antenna. A reciprocal clockwise rotation followed by a combination is applied on the receiver side. It can be shown that the orthogonality of the signals multiplexed on the different modes is preserved thanks to the arrangement of the antennas.

Figure 31 shows the gain of each OAM mode versus link distance in an ideal case of perfectly aligned set of 8 antennas. The gain corresponds to the signal power after combination. The path loss due to distance is not considered in this evaluation.

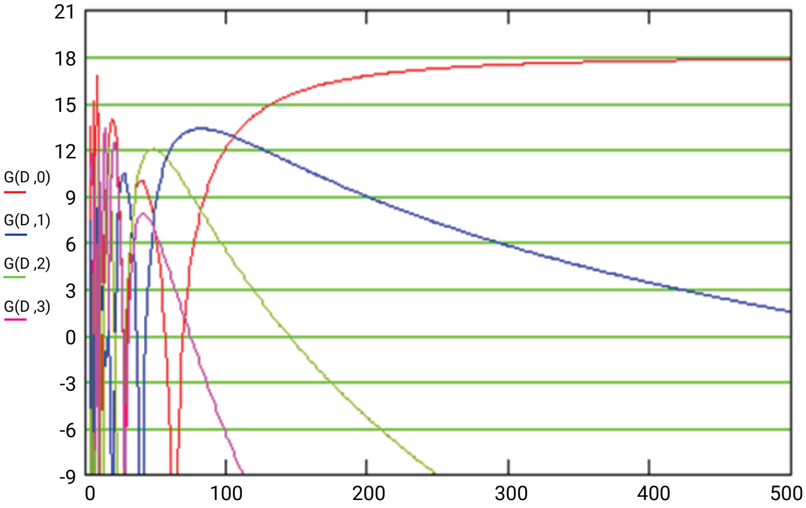


Figure 31 – Gain of each OAM mode vs. distance (m). Antenna array radius R=30 cm, f=80 GHz

The gain of high-order modes rapidly vanishes for increasing hop lengths. Only mode-0 (all antennas in phase) persists, providing a 20.log(8) = 18dB asymptotic gain. Higher modes become unusable beyond a few hundred meters (for a 30 cm antenna array radius). Furthermore, the maxima occur at different distances (e.g., mode 1 and 2 maximum occur around the mode 0 minimum). Switching off the higher modes and using all the TX power for the remaining active modes (e.g., mode 0 and 1) would further improve the system gain.

3.8.2.2 Challenges and Research Directions

The following areas of research are recommended for OAM with 6G systems:

- The most suitable use cases for OAM need to be analyzed in detail, and the potential advantages of OAM in terms of performance, deployment flexibility, and usability as an access technique [177], [178], all need to be weighed against the more conventional techniques of MIMO and beamforming.
- Achieving larger hop lengths, and relaxing the distance/diameter constraints by using alternative or enhanced antenna technologies (multi-ring or lenses), are a must.
- Signal processing to make OAM more robust to impairments: pointing errors and multi-path. Practical antenna designs capable of transmitting and detecting multiple OAM modes with 6G systems is a key challenge.
- Use of RHS for transmission and detection of multiple OAM modes requires further research. The detection method of OAM with holographic beamforming is quite different than beamforming with polarization.
    - In addition, further study needs to be done from the UE side for feasibility.

3.8.2.3 Conclusion

OAM has proven to be an interesting solution for multimode fiber transmissions, but its attractiveness for wireless use needs to be further analyzed. In particular, we need to identify the potential use cases in which OAM could provide significant gains over more conventional approaches based on, for example, MIMO.

4 CONCLUSIONS

This 6G basic radio technology whitepaper identified the evolutionary and revolutionary changes in the fundamental building blocks of the next-generation cellular radios. Successful R&D in these technologies is expected to play a critical role in North America 6G technology leadership.

One of the key aspects of 6G radio technologies is the advancement of communication theories in waveform, modulation, coding and multiple access designs. It was noted that **waveform**, modulation, coding, and multiple access designs for 6G will need to strike appropriate balance between high spectral efficiency, low computation complexity, and power efficiency to meet the demands of 6G wireless systems. For spectral efficiency enhancement, scaling up the QAM modulation order serves as the basic upgrade of **modulation** design in 6G with possible addition of new techniques such as constellation shaping and index modulation. For power efficiency enhancement, various coded modulation schemes have been proposed, in conjunction with single carrier waveforms, to form low PAPR signals that allows efficient PA operations. For area efficiency and processing latency, finding **channel coding** schemes that have favorable performance-complexity tradeoffs may be an important research topic to support the higher peak throughput scaling for 6G. New waveform and **multiple access** designs, such as unsourced random access, are also expected to supplement traditional OFDM and scheduling-based multiple access to enable new use cases such as joint communication and sensing, positioning, zero energy device, etc.

New spectrum is essential for successful deployment of the next generation of mobile networks. 6G is expected to be deployed in new spectrum in upper-mid band and potentially subTHz. Semi-static and dynamic **spectrum sharing** techniques have been identified to share spectrum among multiple services, service providers and/or technologies within overlapping geographical regions for better utilization of spectrum.

New MIMO designs in 6G could enable better coverage, capacity, and energy efficiency for different frequency bands. For **low frequency MIMO** with limited spectrum, it is crucial to improve spectral efficiency considering challenges in antenna size, channel state acquisition, and processing architecture. For **advanced massive MIMO** at mid-band/upper mid-band, cutting-edge research needs to address challenges in faster beam management, channel state acquisition, hardware impairments in cost-effective implementation, and energy efficiency/power consumption for very large number of antennas. **Massively distributed MIMO** needs to address the challenges of efficient synchronous and non-synchronous operations, scalability and interference management as well as access, mobility and robustness.

Reconfigurable Intelligent Surfaces (RISs) represent a groundbreaking innovation in radio technologies, enabling the manipulation of radio environment, where the channel state can be considered as a degree of freedom for waveform, modulation, and coding design. To determine the benefits and challenges of introducing RIS into current communication systems, additional research is necessary to quantify the comparative advantages of deploying RIS versus alternative solutions.

6G **mmWave research** needs to introduce new technologies to enable more advanced and streamlined systems at higher frequency with better coverage and connection reliability. Specific research areas include beam management enhancements, seamless mobility, topology enhancements for densifying network, power-efficient UEs, and greener more power-efficient network implementation.

It is almost inevitable to conclude that 6G and beyond wireless systems will (to a certain extent) start exploring **(sub-)THz** frequency ranges to improve their peak performance, while the successful design and integration of (sub-)THz communications into the wireless networking landscape impose several research and engineering challenges, such as channel modelling, waveform and system design with mobility and beam switching techniques. (Sub-)THz technology can be also a key enabler for other technologies such as **Joint Communication and Sensing (JCAS)**. JCAS can enable new and enhance existing services and add value to 6G system. Cutting edge research faces challenges related to interference, improving line of sight, characterization, evaluation and validation of channel models, and signal designs depending on the sensing objectives and topologies.

6G could benefit from **full duplex** operation that leverages both wide-bandwidth TDD and long-range FDD deployments. In addition to operating in the frequency ranges currently supported by 5G networks, adopting full duplexing schemes in new spectrum for 6G in even higher frequency ranges (e.g., upper-mmW/sub-THz) can both boost system performance, as well as facilitate key 6G use cases such as ultra-precise localization and sensing.

Recent application of **Reconfigurable Holographic Surfaces (RHS)** and **Orbital Angular Momentum (OAM)** in wireless communications has attracted many research interests. Using holographic beamforming is considered as an efficient way to realize ultra-massive MIMO, especially for large antenna arrays. Following the holographic interference principle, the amplitude-controlled method of holographic beamforming can effectively steer the beam towards the desired direction. OAM has proven to be an interesting solution for multimode fiber transmissions, but its application for wireless use needs to be further analyzed to identify the potential use cases in which OAM could provide significant gains over more conventional approaches based on e.g., MIMO.

Building upon the basic radio technologies described here, the second part of the 6G radio technology whitepaper will focus on new AI native wireless design, green communications, and network topology technologies.

5

ABBREVIATIONS AND ACRONYMS

3GPP	3rd Generation Partnership Project
ABP	Adaptive Belief Propagation
AF	Amplify-and-Forward
AFC	Automated Frequency Coordination
AI	Artificial Intelligence
AP	Access Point
APSK	Amplitude and Phase Shift Keying
A-SWNC	Adaptive Way-Sliding Window Random Linear Network Coding
ATSC	Advanced Television System Committee
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BFD	Beam Failure Detection
BICM	Bit-Interleaved Coded Modulation
BMA	Box and Match Algorithm
BMS	Binary-Input Memoryless Symmetric Channels
BPSK	Binary Phase Shift Keying
CAGR	Cumulative Aggregate Growth Rates
Cat-M	Category M
CBRA	Contention-Based Random Access
CBRS	Citizens Broadband Radio Service
CDMA	Code-Division Multiple Access
CFO	Carrier Frequency Offset
CJT	Coherent Joint Transmission
CM	Coded Modulation
C-MTC	Critical Machine-Type Communication
CP	Cyclic Prefix
CPE	Customer Premises Equipment
CPM	Continuous Phase Modulated
CP-OFDM	Cyclic Prefix - Orthogonal Frequency Division Multiplexing
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSI-RS	Channel State Information Reference Signal
CSMAC	Commerce Spectrum Management Advisory Committee
DD	Delay-Doppler
DFT	Discrete Fourier Transform

DFT-s-OFDM	Discrete Fourier Transform spread Orthogonal Frequency Division Multiplexing
DL	Downlink
DPSK	Differential Phase Shift Keying
DRX	Discontinuous Reception
DSA	Dynamic Spectrum Access
DVB	Digital Video Broadcast
EDCA	Enhanced Distributed Channel Access
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
eMBB	Enhanced Mobile Broadband
FBMC	Filter Bank Multi-Carrier
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FDSS	Frequency Domain Spectrum Shaping
FEC	Flexibility of Network Coding
FR1	Frequency Range 1
FR2	Frequency Range 2
FSK	Frequency Shift Keying
FSS	Fixed Satellite Service
F-SWNC	Fixed Way-Sliding Window Random Linear Network Coding
FWA	Fixed Wireless Access
GAA	General Authorized Access
GF	Grid-Free
GFDM	Generalized Frequency Division Multiplexing
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GOES	Geostationary Orbit Environmental Satellites
GRAND	Guessing Random Additive Noise Decoding
HST	High Speed Train
IAB	Integrated Access and Backhaul
IC	Integrated Circuit
ICI	Inter-Carrier Interference
ICS	Integrated Communication and Sensing
IEEE	Institute of Electrical and Electronics Engineers
IFIC	Intermediate Frequency Integrated Circuit
I-FSK	Impulsive Frequency Shift Keying
IIC	Incumbent Informing Capabilities

IoT	Internet of Things
IPC	Interference Protection Criteria
IR-HARQ	Incremental Redundancy Hybrid Automatic Repeat Request
JCAS	Joint Communication and Sensing
KPI	Key Performance Indicator
LAA	Licensed Assisted Access
LBT	Listen-Before-Talk
LDPC	Low Density Parity Check
LIDAR	Light Detection and Ranging
LoS	Line-of-Sight
LPWA	Low Power Wide Area
LP-WUR	Low Power Wake-Up Architecture
LP-WUS	Low Power Wake-Up Signal
LTE	Long-Term Evolution
MA	Multiple Access
MAC	Media Access Control
MC-OTFS	Multi-Carrier Orthogonal Time Frequency Space
MD-MIMO	Massively Distributed Multiple-Input and Multiple-Output
MFSK	Multiple Frequency Shift Keying
MIMO	Multiple-Input and Multiple-Output
ML	Machine Learning
MLD	Maximum Likelihood Decoding
MNO	Mobile Network Operator
MRSS	Multi-Radio Access Technologies Spectrum Sharing
MTC	Machine Type Communication
MUD	Multi-User Detection
MU-MIMO	Multi-User Multiple-Input and Multiple-Output
NB-IoT	Narrowband Internet of Things
NCJT	Non-Coherent Joint Transmission
NCR	Network Controlled Repeater
NES	Network Energy Savings
NIST	National Institute of Science and Technology
NLoS	Non-Line-of-Sight
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NTN	Non-Terrestrial Networks
NULA	Nonuniform Linear Antenna Arrays
NW	Network
OAM	Orbital Angular Momentum

OFDM	Orthogonal Frequency Division Multiplexing
OMA	Orthogonal Multiple Access
OOB	Out-of-Band
OOK	On-Off Keying
ORB	Ordered Reliability Bits
OSD	Ordered Statistics Decoding
OTFS	Orthogonal Time Frequency Space
PA	Power Amplifier
PAL	Priority Access License
PAPR	Peak-to-Average Power Ratio
PAS	Probablistic Amplitude Shaping
PBCH	Physical Broadcast Channel
PD	Photodetectors
PDCCH	Physical Downlink Control Channel
PDCCH-WUS	Physical Downlink Control Channel Wake-Up Signal
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PLE	Path Loss Exponent
PRACH	Physical Random Access Channel
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RAN	Radio Access Network
RAT	Radio Access Technologies
RCS	Radar Cross Section
RF	Radio Frequency
RFIC	Radio Frequency Integrated Chip
RHS	Reconfigurable Holographic Surface
RIS	Reconfigurable Intelligent Surfaces
RLM	Radio Link Monitoring
RLNC	Random Linear Network Coding
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Signal
RSRP	Reference Signal Received Power
RX	Reception
SA TSG	System Aspects Specification Group

SAS	Spectrum Access System
SC-FDE	Single-Carrier Frequency-Domain Equalization
SDM	Space Division Multiplexing
SE	Spectral Efficiency
SFFT	Symplectic Finite Fourier Transform
SINR	Signal-to-Interference-plus-Noise Ratio
SL	Sidelink
SNR	Signal-to-Noise Ratio
SPP	Spiral Phase Plate
SRI	Sensing Allocations
SRS	Sounding Reference Signal
SS	Synchronization Signal
SSB	Synchronization Signal Broadcast
SSSG	Skipping and Search Space Set Group
SWNC	Sliding Window Random Linear Network Coding
TCM	Trellis Coded Modulation
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TDMA	Time-Division Multiple Access
TDPS	Time Domain Pulse Shaping
TF	Time-Frequency
TIA	Transimpedance Amplifiers
TN	Terrestrial Network
TR	Technical Report
TRP	Transmission Reception Point
TRS	Tracking Reference Signal
TX	Transmission
UAV	Uncrewed Aerial Vehicles
UCA	Uniform Circular Arrays
UE	User Equipment
UFMC	Universal Filtered Multicarrier
UK-DRL	Deep Reinforcement Learning-Based Resource Allocation Algorithm
UL	Uplink
ULCG	Uplink Configured-Grant
uMBB	Ultra-Mobile Broadband
UMTS	Universal Mobile Telecommunications Framework
URA	Unsourced Random Access
URLLC	Ultra Reliable and Low Latency Communications
UW	Unique Word

UWB	Ultrawide-Band
V2X	Vehicle-to-Everything
WLAN	Wireless Local-Area Network
WOLA	Weighted Overlap Add
WPAN	Wireless Personal Area Network
WTFC	Wideband Time Frequency Coding
WUS	Wake-Up Signal
XR	Extended Reality
ZT	Zero Tail
ZXM	Zero-Crossing Modulation

6

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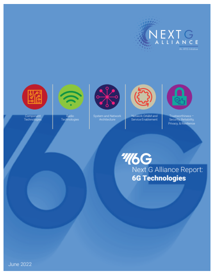
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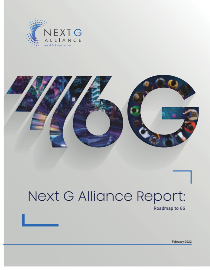
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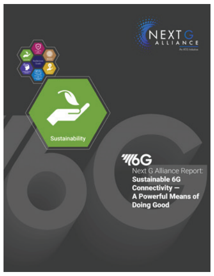
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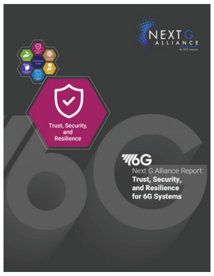
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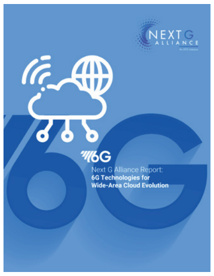
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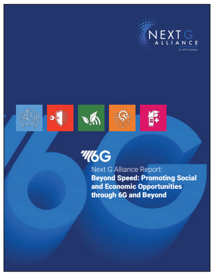
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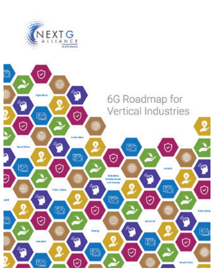
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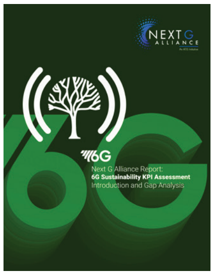
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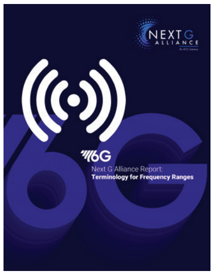
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Published November 2023

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1200 G Street, NW, Suite 500
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