6G Architecting tomorrow

The physical layer foundations powering 6G

White paper

NOKIA

Contents

The 6G physical layer is poised to transform the wireless landscape, serving as the foundation for unprecedented innovation and global connectivity. By integrating robust physical layer fundamentals with trustworthy, standardized AI framework with predictable testing methodologies, the industry is well-positioned to deliver a 6G platform that is not only high-performing and intelligent, but also dependable and future ready. The physical layer foundations outlined in this paper will enable this transformation, setting the stage for the next decade of mobile innovation.

Scope

The world stands on the threshold of a new era in wireless communications - 6G. Going beyond 5G, 6G aims to deliver not only a significantly elevated baseline system performance, but also to embed intelligence and sustainability as core design tenets from day one [1–3]. At the heart of this evolution lies a next-generation radio system built to meet the demands of the 2030s: AI-native, cloud-integrated and spectrum-efficient.

With the development of 6G rapidly moving from research to standardization, August 2025 marks the beginning of the 3GPP RAN working group's meetings focused on the 6G Study Item. This is a pivotal step toward defining the technological foundation of the first 6G standard: 3GPP Release 21. These discussions will evaluate key technology solutions that will shape the core components of 6G, with commercial rollouts expected by 2030.

From the outset, 6G targets to consolidate foundational innovations from 5G-Advanced into a unified, streamlined architecture, maximizing their impact and enabling broad-scale deployment. A key strategic goal is the development of a standalone 6G system with support for Multi-RAT Spectrum Sharing (MRSS), offering a scalable and implementation-friendly approach to deploy 6G in existing FR1 spectrum bands—while still achieving peak performance [7]. In parallel, 6G aims to expand capacity in new mid-band spectrum ranges, notably the upper 6 GHz and 7–15 GHz bands. This expansion is made feasible by a modernized, high-performance physical layer that leverages MRSS and uplink (UL) carrier aggregation.

To support effective deployment in the 7-15 GHz bands using existing 2.5 GHz and 3.5GHz infrastructure, enhancing uplink coverage is also a key priority. This includes optimized user equipment (UE) transmit power capabilities to support power boosting and extended coverage, making 6G deployments more cost-effective and practical [4].

In addition to delivering a superior yet lean radio design optimized for real-world implementation, 6G is expected to natively support AI-driven applications, cloud integration, and ultra-low latency communications—responding to the needs of a rapidly growing and diverse ecosystem of devices and services [5].

To ensure its success, 6G physical layer is being architected to flexibly support a wide range of device types: energy-efficient to meet sustainability goals, streamlined to reduce complexity, and lean with a single-architecture approach and no multiple options, as summarized in Figure 1. From day one, it targets market-relevant features with a unified, future-ready foundation.

Figure 1. 6G physical layer design goals

Flexible
Higher number of ports, agile UE bandwidth adaptation, more UL opportunities and coverage boost

Streamlined
Unified TCI framework for control and data channels, UCI partially reported via L2

EE-friendly signals
SSB and PDCCH embedding DRX/DTX and WUS from day one

Lean
Reduced number of subcarrier spacing per band, no mixed numerologies, from 3 MHz to more than 200 MHz bandwidth

The 6G physical layer will be designed with a strong emphasis on simplicity and efficiency, directly addressing the increasing diversity of connected devices and services. By minimizing options and configurations, 6G day-one deployments can mandate essential capabilities in both devices and networks, simplifying field implementation and ensuring a more robust and reliable network experience.

To meet ambitious performance targets, the 6G physical layer toolbox integrates key enablers such as spectrum access, wider channel bandwidths, and modulation and coding schemes that optimize spectral efficiency. Enhancements in multiple-input multiple-output (MIMO) technology will play a central role in delivering significantly higher data rates and network capacity.

This white paper focuses on these foundational physical layer components, which will define the baseline performance of the 6G air interface. Advancements in MIMO will serve as critical building blocks for future enhancements and broader system evolution throughout the 6G lifecycle.

Physical layer basic design

Numerology and frame structure

The proposed 6G frame structure streamlines and optimizes network performance and uses a single, unified approach. To ensure a seamless transition between 5G and 6G without compromising network performance, Nokia recommends Multi-RAT Spectrum Sharing (MRSS) and 6G Carrier Aggregation (CA) as preferred solutions [7]. The approach in 6G involves supporting a wideband carrier with a bandwidth of up to 400 MHz, utilizing larger Fast Fourier Transform (FFT) sizes (8k or 16k). This approach offers several advantages over current 5G CA techniques, for example, smaller overhead, reduced system complexity, and better uplink coverage.

The 6G numerology must ensure forward compatibility to support flexible bandwidth configurations across all releases, within predefined minimum and maximum limits. We propose setting 3 MHz as the smallest UE bandwidth option to facilitate the introduction of LPWA (Low Power Wide Area) at any release. Native LPWA support should be integrated into key design elements, such as the synchronization signal block, to ensure seamless and efficient LPWA functionality without compromising mobile broadband operations.

To ensure seamless coexistence between 5G and 6G (e.g., in MRSS), we propose retaining 5G-defined subcarrier spacings in 6G. To streamline 6G further, system complexity can be reduced by minimizing the number of sub-carrier spacing (SCS) options per band/range. Additionally, eliminating mixed numerology and extended cyclic prefix (CP) length simplifies implementation and reduces testing overhead.

Alongside FDD operation, enhancements to frame structure and dynamic TDD are needed to support key 6G objectives such as network energy efficiency and sub-band full duplex. This work will build on the 5G-Advanced framework, while improving and simplifying it to unlock the full potential of 6G. These improvements aim to reduce unnecessary complexity, enhance UE power-saving opportunities, and ensure seamless day-one support for all UEs.

Waveforms and modulation schemes

While LTE uses Discrete Fourier Transform-Spread-Orthogonal Frequency Division Multiplexing (DFT-s-OFDM) as the uplink waveform, 5G NR uplink employs either the DFT-s-OFDM or the Cyclic Prefix-Orthogonal Frequency Division Multiplexing (DP-OFDM) for its uplink waveform. This shift introduced a new UL consideration: MIMO precoding with CP-OFDM, which can increase the peak-to-average power ratio (PAPR) of the transmitted signal and thereby diminish UL MIMO coverage (see subsection “Enhancement in transmit power”).

Though DFT-s-OFDM is only supported for rank 1, its superior robustness to Doppler shifts and multipath fading allows for better signal reception in challenging areas. Therefore 5G NR has introduced dynamic waveform switching in Rel-18 where the selection between CP-OFDM and DFT-s-OFDM may be based on trade-off between spectral efficiency and coverage.

The uplink MIMO precoding matrix (TPMI) depends on the UE’s coherence capability. For noncoherent UEs, transmitted signals remain independent. This enables a key advantage for 6G: the coverage and low PAPR benefits of DFT-s-OFDM can be extended to higher-rank uplink MIMO, further improving overall network performance. Additionally, support for coherent uplink transmissions from CPEs can enhance Fixed Wireless Access (FWA) performance and coverage.

The technology proposal encompasses UE transmit power capabilities such as a higher default power class for TDD, increased PA dimensioning, reducing transmit power backoffs, and partially coherent SU-MIMO. These are a few of the new capabilities, see the section “Coverage enhancements” and Table 1, below, for a more complete list.

Control channels

The Physical Downlink Control Channel (PDCCH) is a crucial component of cellular networks as it is used for scheduling and resource allocation, granting access, and carries Hybrid Automatic Repeat Request (HARQ) feedback, paging information and system information. The 6G day-one PDCCH design for energy saving focuses on minimizing power consumption in the UE by optimizing the way it monitors downlink control channels.

In general, devices consume tens of milliwatts in RRC idle/inactive state and hundreds of milliwatts in RRC connected state. Designs for improving energy efficiency and energy savings are necessary to prolong device battery life and user experience. This becomes especially critical for UEs that lack a continuous power source, such as those powered by small rechargeable or single coin cell batteries. In many use cases, sensors and actuators are widely deployed for monitoring, measuring, charging, and other functions, making energy-efficient design a key enabler of their long-term operation.

Thus, from 6G day one, UEs should utilize power-saving features like Discontinuous Reception/ Transmission (DRX/DTX), Wake-up Signal (WUS) and adaptive PDCCH monitoring. These features aim to minimize UE active time by reducing unnecessary PDCCH monitoring, thereby minimizing UE power consumption, which translates to longer battery life and a more energy-efficient network overall. The baseline structure of PDCCH may exploit the well-tested fundamentals of 5G PDCCH, with configurable control resource sets and with a PDCCH transmission composed of varying number of control channel elements, the basic building blocks of PDCCH.

The Physical Uplink Control Channel (PUCCH) is also crucial and is responsible for carrying uplink control information (UCI) from the UE to the network. This includes Hybrid Automatic Repeat Request (HARQ) acknowledgements, scheduling requests (SR), and channel state information (CSI) reports.

PUCCH plays a key role in supporting reliable communication, dynamic resource allocation, and advanced link adaptation. In 5G NR, there are five PUCCH formats (Format 0 to Format 4), optimized for different payload sizes and latency/reliability needs. In 6G, PUCCH will continue to evolve to accommodate greater flexibility and higher reliability, e.g., introducing streamlined UCI reporting with simplified timeline and multiplexing specifications.

UCI multiplexing, prioritization and PUCCH resource determination are rather complex in 5G NR with a larger number of overlapping cases to manage. In 6G, these procedures could be simplified, for example, by relocating CSI reporting to PUSCH.

Reference signals

To accommodate 6G expanded bandwidth and new functionalities, the Synchronization Signal Block (SSB) will undergo significant modifications. These changes will include adjustments to the SSB structure and content to support the unified Transmission Control Information (TCI) framework and various scenarios such as initial cell selection, cell reselection, and mobility, all while ensuring network energy savings.

Reducing reference signals, including SSBs, will be key to a leaner, always available 6G network, offering flexibility and significant energy savings by increasing cell sleep opportunities. Relaxing the 5G standalone requirement for 20ms SSB transmission periodicity, while avoiding excessive UE complexity, is crucial. Furthermore, reducing essential system information (e.g., SIB1) transmission will substantially enhance efficiency. The adoption of on-demand and load-based provisioning for SSBs, synchronization signals, system information, PRACH, and paging will be essential for 6G from day one [6].

Reference signals are integral to MIMO operation, serving purposes such as channel estimation, synchronization, phase tracking, and more. In addition to existing signals like PSS, SSS, CSI-RS, and SRS, 5G NR introduced new reference signals to enhance data rates and reduce latency. These include the Phase Tracking Reference Signal, PBCH Reference Signal, Time/Frequency Tracking Reference Signal, and Demodulation Reference Signal for PDCCH and PDSCH.

6G will introduce enhancements to various reference signals, including PxSCH demodulation reference signals (DMRS), CSI-RS, and UL SRS, to optimize resource utilization and improve multi-user MIMO (MU-MIMO) performance.

For PxSCH DMRS, 6G allows for flexible distribution of frequency and time resources, supporting an increased number of orthogonal DMRS antenna ports (up to 48 or even higher) both in DL and UL. Increased numbers of orthogonal DMRS antenna ports enables correspondingly higher numbers of simultaneous transmission layers in the cell to boost significantly both cell and cell edge spectral efficiency.

The denser the DMRS pattern, the better the channel estimation, though at the cost of reduced spectral efficiency. 6G offers the potential to reduce the density of the DMRS while maintaining demodulation performance by using AI/ML-based receivers such as DeepRx. These receivers use deep neural networks to perform accurate channel estimation and signal detection even under sparse reference signal configurations by leveraging learned models rather than purely deterministic algorithms.

CSI-RS, used for DL channel state information acquisition, is meant to support a significantly higher number of antenna ports, exceeding 128, to support gNBs with extreme capabilities in terms of a very high number of transceiver units (up to 256 or 512) specifically envisioned for upper 6 GHz and 7 GHz system operation. This enables more precise channel estimation and improved MU-MIMO performance. Additionally, enhancements for time and frequency tracking ensure accurate synchronization and signal reception.

As 6G scales up the antenna count and bandwidth, efficient CSI feedback becomes increasingly critical, when the downlink channel must be estimated by the UE and fed back to the network. 5G NR traditional CSI compression methods rely on codebooks, which quantize the channel into a limited set of predefined entries. While this approach is standardized and low complexity, its scalability is limited in massive MIMO settings. 6G opens up for AI/ML CSI compression techniques to offer a more flexible and efficient alternative which leverages deep learning models to learn compact, nonlinear representations of CSI tailored to specific deployment scenarios. This approach significantly reduces feedback overhead while maintaining channel reconstruction quality [8].

UL SRS, used for uplink channel estimation, also benefits from increased antenna port support, exceeding eight for CPE/FWA applications. This allows for more efficient uplink resource allocation and improved SU-MIMO and MU-MIMO performance. Furthermore, antenna-switching enhancements for existing and new configurations, along with reduced overhead for xTyR antenna configurations (e.g., 1T2R, 1T4R, 1T8R), further optimize resource utilization.

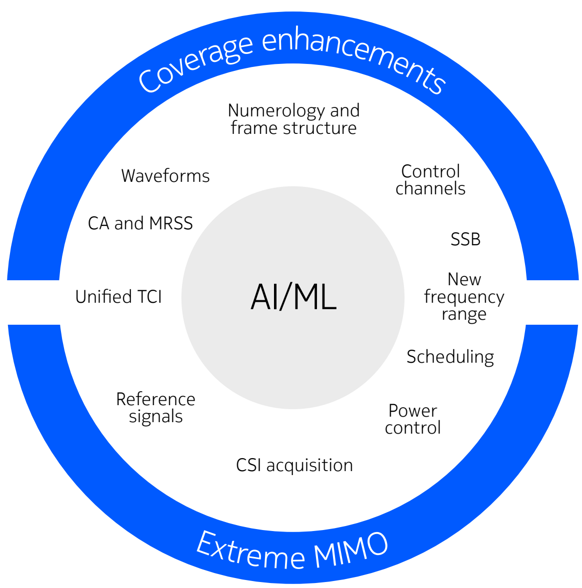
6G enhancements in PxSCH DMRS, CSI-RS and UL SRS aim at optimizing resource utilization and improving MU-MIMO performance. A breakdown of the benefits is summarized in Table 1.

Table 1. Reference signal enhancements for 6G and their respective benefits.

RS enhancements for 6G	Benefits for 6G
PxSCH DMRS	Increase up to 48 orthogonal DMRS antenna ports for DL and UL, which will increase the number of simultaneous transmission layers and boost spectral efficiency
CSI-RS	Increase up to 256 antenna ports, which will improve precision of channel estimation and MU-MIMO performance
UL SRS	Increase up to 16 antenna ports improving SU-MIMO (e.g., CPE/FWA) and MU-MIMO performance

To conclude this section on physical layer basic design, Figure 2 illustrates the three primary physical layer components for 6G: enhanced coverage, extreme MIMO, and expanded spectrum. Each of these goals is supported by a set of key building blocks, including the unified TCI framework, waveforms, control and data channels, CSI acquisition, and many more, which together enable superior design and performance. A fundamental game changer for 6G will be to assess how to natively integrate AI/ML within these building blocks. This integration will build upon the 5G-Advanced AI/ML framework while exploring new use cases.

Figure 2. 6G physical layer building blocks



6G MIMO technology

MIMO and beamforming (BF) are critical technologies for achieving a high-performing physical layer in terms of coverage reliability and spectral efficiency.

The motivation for 6G MIMO stems from the need to overcome the limitations of 5G and deliver a significantly enhanced mobile experience. 6G MIMO seeks to simplify the framework, offer better performance, improve scalability of deployment, and reduce deployment costs as well as power consumption compared to 5G. 6G aims at significantly increasing system spectral efficiency by introducing extremely high spatial multiplexing capabilities and user spectral efficiency, particularly at the cell edge. This will enable higher data rates and better coverage. Furthermore, 6G is streamlining the network design to make it more sustainable and accessible.

6G MIMO is designed to support all existing MIMO and beamforming scenarios from 5G-Advanced, including intra-cell and inter-cell single- and multi-TRP deployment configurations. This ensures seamless integration and future proofing for advanced technologies like distributed MIMO (dMIMO) and multi-TRP (mTRP) schemes. This will be crucial for delivering the high data rates and low latency expected in 6G. By addressing these key motivations, 6G MIMO aims to lay the foundation for a more robust, efficient, and future-proof mobile network that can meet the demands of the next generation of wireless communication technologies.

Main components

6G is poised to revolutionize wireless communication with its advanced MIMO capabilities. At the heart of this revolution lies a unified Transmission and Control Information (TCI) framework. The unified TCI framework was defined in 5G NR Rel-17 to provide Quasi Co-Location (QCL) relations for both DL and UL in the same framework with DCI-based updates. Rel-18 extended this framework to support mTRP operation. 6G may increase the number of indicated TCI states, the applicability to other signals and channels, and much more to streamline resource allocation and ensure a seamless user experience across both DL and UL communications, including beam management. The 6G unified TCI framework enhancements will support a vast bandwidth, enable significantly higher end-user experienced data rates, when needed, as well as a wider range of applications.

6G will leverage advanced MIMO techniques for both DL and UL communication. For DL MIMO, SU-MIMO will support up to 256 ports, utilizing both SRS-based and codebook-based approaches (Type I and Type II extensions). MU-MIMO will enable simultaneous transmission to multiple users, also leveraging both codebook-based as well as SRS-based CSI acquisition techniques. On the UL side, codebook-based UL MIMO will be the baseline, supporting up to 16 UL ports per UE. Non-codebook-based UL MIMO promises potentially significant benefits in poor path loss conditions, but at the cost of higher UE implementation complexity. Whenever possible, dynamic mMIMO muting with fast deactivation of Tx antenna ports can be employed as an essential network energy saving feature when using the large antenna arrays envisioned in 6G. This requires a flexible CSI and CSI-RS framework tailored to overhead reduction.

To ensure efficient and dynamic resource allocation, 6G may utilize an event-based CSI reporting framework in addition to legacy periodic, semi-persistent and aperiodic non-event triggered reporting. Furthermore, 6G will support Coordinated Joint Transmission (CJT) and multi-TRP (Transmit Receive Point) configurations, enhancing coverage and capacity. These features, combined with the advanced MIMO capabilities, will pave the way to a new era of wireless communication, characterized by unprecedented speed, reliability and capacity.

The integration of AI/ML is expected to be a pivotal element in 6G, enabling the optimization of the physical layer design. The 6G study item will evaluate the performance of AI/ML applied to use cases such as CSI feedback (prediction and compression), reference signals, transceivers, mobility, beam management, random access, power control, precoding and more. The ultimate goal is to enhance the overall performance and efficiency of the network. Further details can be found in [2, 8, 9, 10].

AI-powered air-interface solutions introduce adaptive and stochastic behaviors that go beyond the capabilities of traditional, deterministic testing methods. Ensuring predictable and trusted performance in such systems requires a new lifecycle approach, encompassing testing, validation, monitoring, and ongoing adaptation [11]. This shift began with the development of a robust requirements and testing framework for AI in 5G-Advanced and will evolve with the scalable deployment of 6G use cases.

These are some of the key components of 6G, highlighting the advancements in bandwidth, MIMO, CSI reporting, and the integration of AI/ML for enhanced performance and efficiency.

Comparing 5G and 6G day-one MIMO performance

Some of the key differentiators between 5G and 6G day one will be the number of CSI-RS ports, the number of layers, and utilization of Type II feedback, as summarized in Table 2.

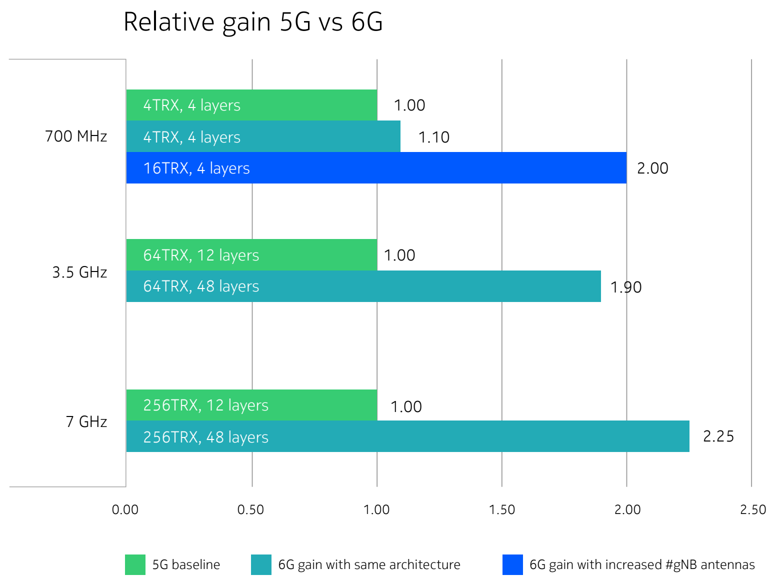
Table 2. 5G and 6G MIMO parameters and DL-derived and UL-derived CSI acquisition

	5G Deployed R15/16	5G Specification R19	6G Day-one
CSI-RS	32 ports	128 ports	256 ports
PxSCH DMRS (#layers)	12	24	48
DL CSI acquisition	Type I	Type II	Type II
UL CSI acquisition	4-ports SRS	8-port SRS	16-port SRS

Spectral efficiency comparisons between 5G performance and 6G day-one expectations are presented in Figure 3, derived from advanced system-level simulations. The analysis assumes DL-derived CSI acquisition for 5G and ensures fair comparisons by using identical carrier frequency, deployment scenario, bandwidth and array configurations. Notably, 6G's higher number of transceiver ports (mapped to 8-port CRI in 5G case to enable the comparison) and higher number of layers (48 in 6G vs 12 in 5G), coupled with enhanced multi-user MIMO exploitation through higher-resolution Type II CSI feedback (not deployed in 5G) contribute to its gains. The results are for an urban macrocell (UMa) scenario with a 500-meter inter-site distance (ISD). The number of transceivers (TRX) used is 4, 64, and 256 for the 700 MHz, 3.5 GHz, and upper 6–7 GHz bands, respectively.

6G provides significant DL spectral efficiency gains over 5G for all three frequency bands [12]. The main contributing factors are an increased number of MIMO layers (from 12 to 48) and CSI-RS ports (from 32 to 256), and a more accurate CSI feedback scheme with Type II.

Figure 3. DL MIMO gains for 6G day-one compared to 5G-deployed performance



Low bands (700 MHz)

When comparing four transmit/receive (TRX) and four layers, Type II feedback provides approximately a 10% improvement in mean spectral efficiency for multi-user MIMO (MU-MIMO) spatial throughput (sTRP) scenarios. However, increasing array configuration parameters (i.e., increasing from 4 TRX to 16 TRX at 700 MHz) can lead to more than double the spectral efficiency for both mean and cell-edge UE. Furthermore, CJT is expected to yield significant gains in this frequency range as it allows for more efficient use of multiple antennas and improved coverage, especially at cell edges.

Mid-bands (2.5~3.5 GHz)

The MU-MIMO sTRP spectral efficiency gain for apples-to-apples comparisons is expected to be more substantial at mid-bands compared to low bands, reaching up to 90% for mean spectral efficiency with cell edge spectral efficiency gain greater than or equal to 1. The larger gains in the mid-band are due to two factors:

1. The larger array sizes deployed at mid-band are much better suited for to MU-MIMO than the small arrays deployed in the low bands
2. The use of the higher CSI resolution accuracy from the Type II CSI has a bigger performance benefit with MU-MIMO but only a small benefit when using SU-MIMO (the dominant mode at low band).

Upper mid-bands (7 GHz)

Type II feedback provides even greater gains at high bands, resulting in more than a factor of two improvement in mean spectral efficiency with cell edge spectral efficiency gain greater than or equal to 1. In this case, 256 TRX for 5G performance consists of 8-port CRI Type-I where 256 TRX is mapped to 8 TX port.

The field test analysis of a recent Nokia-Telia trial [4] underscores comparable performance with the concept radios in the upper 6 GHz bands versus the commercial radios in the 3.6 GHz band. This result will enable significant additional capacity in mobile networks by reusing the existing macro-cellular infrastructure to ensure rapid, cost-efficient and sustainable rollouts.

As a summary, the significant potential of 6G MIMO to drive substantial improvements in network performance and user experience across various frequency bands and deployment scenarios is paving the way for a more efficient and robust wireless communication ecosystem. Furthermore, the presented results are only a baseline from the perspective of physical layer and MIMO performance for day one—other innovative enhancements are still expected to come throughout the 6G Study item [13][14].

Coverage enhancements for 6G

Traditionally, mobile networks have been optimized for DL traffic while network coverage is often limited in the UL direction especially in TDD configurations that generally prioritize DL over UL. After all, we've spent years consuming content-streaming videos, downloading files and browsing websites. But AI is flipping the script. Our devices aren't just passive receivers of information; they're active participants in a complex dance of data exchange [15]. Instantaneous UL speeds will increase, driven by rising data volumes and AI-powered content creation, such as generating AI-enhanced images. This means UL coverage remains a major area for improvement.

The deployment of 6G networks will also extend to new frequency bands at upper 6GHz and in the range of 7 to 15 GHz. To ensure an affordable rollout of 6G networks, it is crucial to efficiently reuse existing cell sites that currently operate on lower frequency bands like 2.5 GHz or 3.5 GHz. To achieve this, the 6G coverage on the new frequency bands of upper 6 GHz and 7–8 GHz must match the coverage provided by the 3.5 GHz band, despite the larger signal propagation losses requiring roughly a 6 dB increase in link budget.

By expanding coverage in these higher frequency bands, 6G unlocks a vast spectrum of possibilities for enhanced data rates and capacity, paving the way for a truly transformative mobile experience. This shift will allow for more efficient use of existing infrastructure and unleash the full potential of higher frequency bands, driving the next generation of mobile communication. Finally, good coverage is essential for all data rates in all scenarios—not only for the cell edge conditions on the new frequency bands—and it is a core feature for a successful radio access technology [4].

Key coverage enhancements

6G will incorporate several key components to enhance uplink coverage. 6G aims to drive significant advancements in both base station and user equipment capabilities to ensure robust and efficient communication in the new frequency ranges. When considering coverage, transmission power, transmission time and applied antenna solutions are the key factors. 6G will leverage all of these for enhancing coverage.

Advances in antenna solutions

Focusing first on base station reception improvements, 6G base stations will deploy larger antenna arrays that are feasible at higher frequencies, enhancing their capabilities for Rx beamforming and compensating partially for the increased path loss at the higher frequency bands. Additionally, deployments with mTRP will be natively incorporated in 6G from day one, allowing for the efficient use of antennas and improving cell coverage.

6G will also leverage the improved MIMO capabilities of UEs, including partially coherent single user MIMO transmission. For FWA UEs, coherent MIMO transmission can be exploited as well as larger UE array sizes (e.g., up to 16 port arrays in the 7–15 GHz range). The improved MIMO capabilities of UEs will boost both the data rates and coverage.

Enhancements in transmit power

The most straightforward way to improve UL coverage is to increase the UE transmission power capabilities, either by adjusting the existing UE RF requirements of current UE power classes or adopting high power classes (such as PC2, PC1.5). When considering the recent advances in UE capabilities, 6G will aim for larger power amplifier dimensioning at the UE. This facilitates, for example, an increased default power class and reduced output power backoffs. Another way to boost available UE Tx power is to define specific UE RF requirements based on UE channel bandwidth, while other UE RF requirements are defined based on BS channel bandwidth that may be wider.

The significantly increased maximum transmission power of UEs improves both data rates as well as coverage without extended transmissions times that in turn may reduce spectral efficiency and UE sleep duration. Power boosting and high-power classes are particularly beneficial in TDD scenarios, where the natural duty cycle based on existing DL/UL ratio is in place.

6G will also use CP-OFDM in UL thanks to its natural suitability for scenarios with high spectrum efficiency. However, the transmitted signal of CP-OFDM has high power variations, which cause the UE's power amplifier to operate far from its saturation point. This in turn reduces the signal's maximum transmit power level.

For coverage limited scenarios, 6G will also support, similarly to 5G, DFT-s-OFDM waveform. DFT-s-OFDM transmission characteristically has lower power variations allowing the UE's power amplifier to be operated closer to the saturation point. Higher transmission power can be used for the uplink transmission while fulfilling the necessary requirements for the transmitted signal quality.

The utilization of the power amplifier can be improved even further with coverage-optimized waveforms like frequency domain spectrum shaping with spectrum extension (FDSS-SE) DFT-s-OFDM that are optimized to have minimal power variations. DFT-s-OFDM capabilities will also be enhanced to support SU-MIMO with multi-layer transmissions. Finally, dynamic switching of OFDM waveforms facilitates the use of the most efficient waveform for the situation at hand, without an extensive amount of waveform reconfigurations.

Enhancements in transmission time

In addition to higher transmission power, the coverage can also be improved with extended transmission time. 6G's uplink resource allocation in the time domain will natively and flexibly support longer transmissions times, e.g., transmissions exceeding slot duration. This, for instance, allows a single transport block to be transmitted with the transmission time extending over multiple slots.

Typically, in TDD, most slots are allocated for downlink transmission, and the uplink has only a few slots. This sets challenging limits for a practically feasible transmission time. On the other hand, a larger number of uplink slots would cut away downlink capacity. To solve the problem, advanced duplexing techniques such as sub-band frequency division will be considered for 6G. The versatile carrier aggregation of 6G can also be utilized to increase UE transmission opportunities for enhanced uplink coverage. While the UE receives downlink data through a high-capacity carrier, e.g., on a new 6G frequency band, it may have its uplink configured on a narrower uplink-weighted or uplink-only carrier facilitating longer transmission times.

There will also be advances to the signal structures for improving coverage. For example, to also ensure reliable initial access on the upper frequency bands, new long Physical Random Access Channel formats will be considered. The formats may be based on 5 kHz subcarrier spacing and facilitate propagation delays in the range that is suitable for frequency bands at the upper 6 GHz or 7–15 GHz frequency ranges.

Comparing 5G and 6G

As discussed above, there are a considerable number of key components for improving crucially important uplink coverage. These components are based on advances in antenna solutions, transmission power and in transmission time, and all of them will contribute to the enhanced coverage of 6G. For convenience, we have summarized them in Table 3 together with a brief description of their impact.

Table 3. 6G key coverage enhancement components

Feature	Impact
Enhanced antenna solutions	
Larger base station antenna arrays	Generic improvement for both coverage as well as UE data rates with an increased number of antennas and more efficient use of them
Native multi-TRP support	
Improving UE SU-MIMO	
UE transmit power advances	
Higher default UE power class	Generic improvement for both coverage as well as UE data rates whenever the UE is on transmit power limit, e.g., due to cell edge condition or wide resource allocation in frequency
Reduced output power backoffs with power amplifier dimensioning and changed UE RF requirements	
Coverage optimized waveforms like FDSS/FDSS-SE DFT-s-OFDM	Improved coverage for low order modulations
Improvements in transmission time and signal structure	
Transport block over multiple slots, joint channel estimation	Improved coverage for low data rates
Advanced duplexing, aggregating TDD carrier with UL weighted carrier	Features facilitate availability of sufficient uplink resources
RACH coverage enhancements	Feature facilitates reliable initial access on new 6G frequency bands

In the Figure 4, we depict the coverage gains achievable in the 3.5 GHz frequency band with the components providing generic performance advances. The gains add up to an impressive 6 dB improvement. In Figure 5, we show gain estimates for the features that are applicable for certain transmission configurations such as specific modulation order. Overall, the impressive lineup of coverage enhancement mechanisms will play a crucial role in building a more robust, efficient and user-friendly 6G network, enabling a truly transformative mobile experience.

Figure 4. 6G uplink coverage gains vs. 5G for 3.5 GHz TDD scenario (generic components)

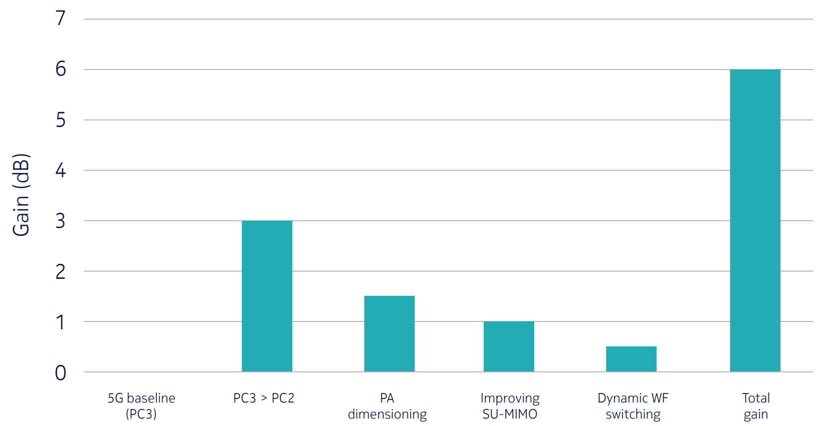
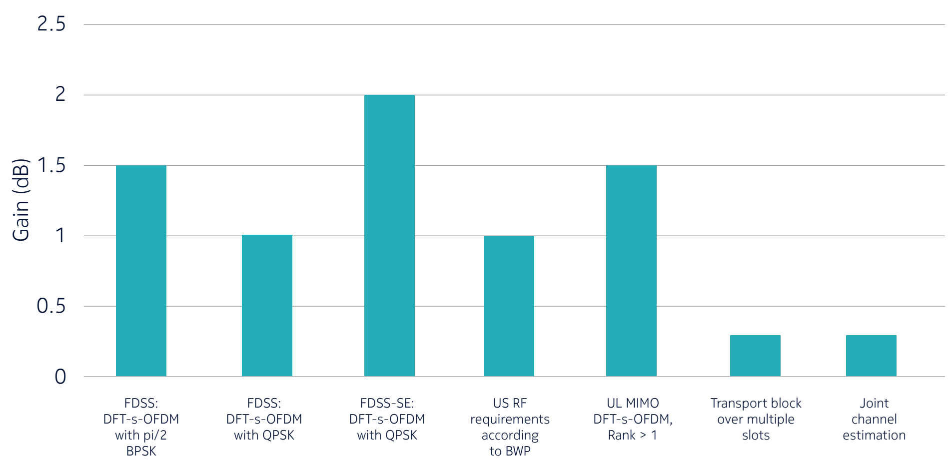


Figure 5: 6G uplink coverage gain vs. 5G for specific transmission components



Summary

As the development of 6G enters an exciting phase with the start of the 3GPP 6G Release 20 meetings, the physical layer stands out as the foundation upon which the performance, scalability and intelligence of future networks will be built. From enhanced coverage and extreme MIMO to expanded spectrum access, 6G aims to deliver superior baseline capabilities through a streamlined and lean radio design. These advancements are designed to support real-world deployment efficiency from day one.

Together, the physical layer enhancements enable more efficient use of spectrum, reduce resource overhead, and significantly improve MU-MIMO operation resulting in higher data rates, better coverage, and improved spectral efficiency across the network.

A defining aspect of 6G will be its native integration of AI/ML to improve performance, adaptability and system intelligence. Whether enabling reduced DMRS density, compressed CSI feedback, or adaptive radio behaviors, AI will augment the capabilities of the physical layer. Nevertheless, these benefits come with new challenges in ensuring reliability, testability and conformance. The requirements will be built upon the framework defined in 5G-Advanced to support the stochastic and evolving nature of AI-driven features with a continuous AI lifecycle management from training to adaptation and monitoring across all 6G releases.

Beyond technical advances, 6G is also responding to shifts in traffic demand and the economic viability of new technologies. It is expected to drive both performance leaps and network efficiency, while creating top-line revenue opportunities and enabling entirely new services. The key value pillars of 6G will include improved user experience, enhanced throughput, broader coverage, energy efficiency, security, and reduced operational costs, which will usher in an era of more intelligent, sustainable and commercially viable wireless connectivity.

The 6G physical layer is therefore poised to transform the wireless landscape, forming the basis for unprecedented innovation and global connectivity. By combining robust physical layer fundamentals with trustworthy, standardized AI integration and scalable testing methodologies, the industry is well-positioned to deliver a 6G platform that is not only highly performing and intelligent, but also dependable and future ready. The physical layer foundations described in this paper will enable this transformation, laying the groundwork for the next decade of mobile innovation.

Abbreviations

AI	Artificial intelligence
BF	Beamforming
BS	Base station
CA	Carrier aggregation
CJT	Coordinated joint transmission
CP	Cyclic prefix
CPE	Customer premises equipment
CP-OFDM	Cyclic prefix-orthogonal frequency division multiplexing
CRI	CSI-RS indicator
CSI	Channel state information
CSI-RS	CSI reference signal
DFT-s-OFDM	Discrete Fourier transform-spread-orthogonal frequency division multiplexing
DL	Downlink
dMIMO	Distributed MIMO
DMRS	Demodulation reference signal
DRX/DTX	Discontinuous reception/ transmission
FDSS-SE	Frequency domain spectrum shaping with spectrum extension
FFT	Fast Fourier transform
FWA	Fixed wireless access
gNB	Next-generation node B (5G BS)
HARQ	Hybrid automatic repeat request
LPWA	Low-power wide area
LTE	Long-term evolution
MIMO	Multiple-input multiple-output
ML	Machine learning
MRSS	Multi-RAT spectrum sharing
mTRP	Multi-TRP
MU-MIMO	Multi-user MIMO
NR	New radio
PAPR	Peak-to-average power ratio
PDCCH	Physical downlink control channel
PDSCH	Physical data shared channel
PHY	Physical layer
PSS	Primary synchronization signal
QCL	Quasi Co-Location
QPSK	Quadrature phase shift keying
RACH	Random access channel
RAT	Radio access technology
RF	Radio frequency
SCS	Sub-carrier spacing
SSB	Synchronization signal block
SRS	Sounding reference signal
SSS	Secondary synchronization signal
sTRP	Spatial throughput
SU-MIMO	Single user MIMO
TCI	Transmission and control information
TDD	Time division duplex
TPMI	Transmitted precoding matrix indicator
TRP	Transmit receive point
TRX	Transceivers
UE	User equipment
UL	Uplink
UMa	Urban macrocell
WUS	Wakeup signal

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