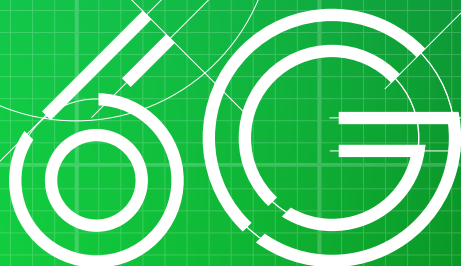


NOKIA



The potential of upper 6 GHz for 6G: Field insights and comparison with 3.6 GHz

White paper



Architecting
tomorrow

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Executive summary

Wireless traffic growth is fueled by the continual rise in 5G adoption among both consumers and businesses. New services and new business models demand continuous availability of high-performance, zero-downtime networks to serve the most demanding use cases. This has a direct impact on radio access network (RAN) capacity requirements. Over time, the current capacity will not be sufficient and new spectrum bands will be essential to ensure a substantial increase in network capacity while maintaining efficiency and sustainability.

The upper 6 GHz spectrum band (6425–7125 MHz) allocated for mobile services and agreed to by several regions of the world at the World Radio Conference in 2023, is emerging as a key resource in many countries to meet the capacity crunch towards 2030 and prepare initial deployments of the new generation of mobile technology, 6G.

While new spectrum is always welcome to improve mobile broadband service, not all spectrum bands are equally attractive for mobile operators. Critical to the attractiveness of the upper 6 GHz band is the ability to build economically viable and high-performing networks, for example, by leveraging the existing site grid on which current networks are deployed.

To validate the feasibility of the upper 6 GHz spectrum for providing mobile broadband services, Nokia and Telia have collaborated to test its radio capabilities in both indoor and outdoor environments, leveraging the existing macro network infrastructure. The findings demonstrate that the upper 6 GHz band is not just a theoretical option but a practical and sustainable solution suitable for initial 6G deployment. These results provide valuable insights for global regulatory bodies and the telecommunications industry, reinforcing confidence in the upper 6 GHz band's suitability for next-generation mobile networks.

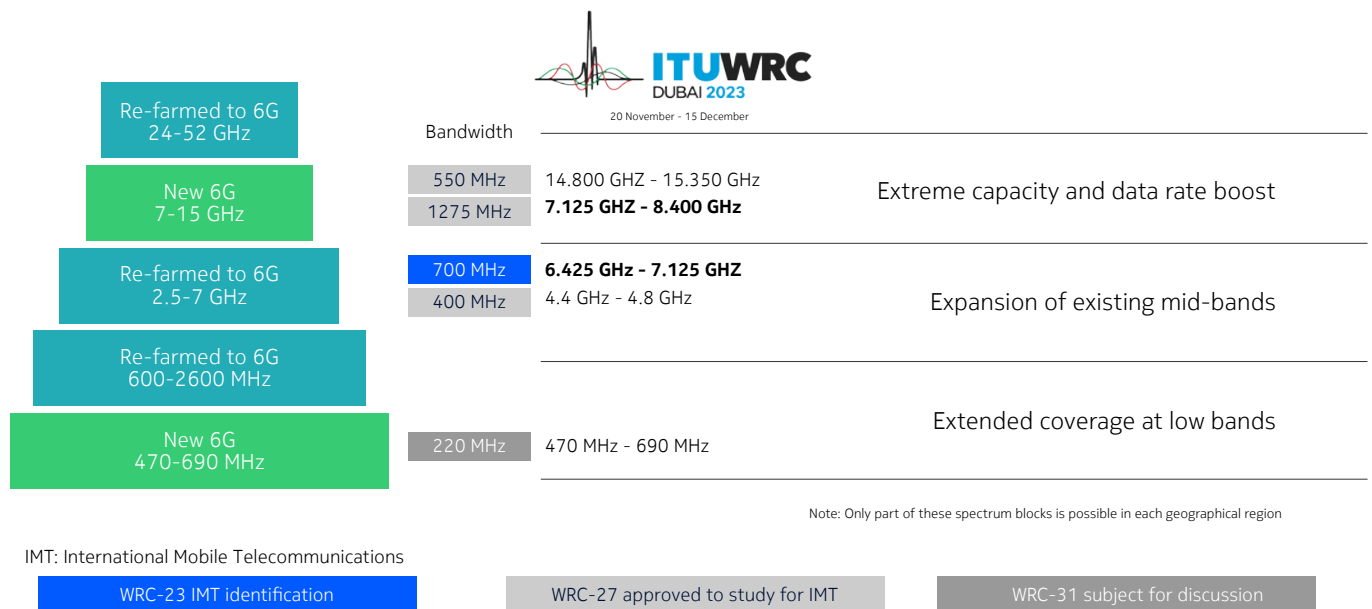
Nokia is committed to continuously enhancing its product and technology roadmaps to enable our customers to leverage new spectrum bands as they become available and ensure a future-proof network evolution to 6G. Following the tests in Finland with Telia, we continue evaluating the upper 6 GHz band capabilities in different capital cities, exploring collaborations with operators across Europe and worldwide to address real-life conditions and evaluate challenges and opportunities. Nokia is ready to supply the demand in the band and provide equipment to ensure that upper 6 GHz can deliver critical capacity for growing data demand.

Upper 6 GHz is an important building block for the success of 6G

Numerous reports predict that a surge in AI usage will be fueling unprecedented data traffic growth. A Bell Labs Consulting study from October 2024 [1] projects that mobile traffic will increase six to nine times by 2033. Meanwhile, a 2024 OMDIA study [2] highlights a shift in traffic sources, with the traditional 20%+ year-over-year growth evolving due to the increasing impact of AI-enabled applications. Adding to this, a GSMA Intelligence report from March 2025 [3] underscores the critical role of edge computing for AI, as many AI use cases will require workloads to be processed closer to end users to ensure lower latency, enhanced data privacy, improved resilience and greater bandwidth efficiency.

To meet this rising demand, additional upper mid-band spectrum is needed to enhance the existing 5G infrastructure, allowing cost-effective upgrades using the current 5G grid. For the initial deployment of 6G, spectrum in the upper 6 GHz and 7–8 GHz bands will be crucial to support future connectivity needs. These bands will expand capacity in densely populated areas, addressing growing data traffic and the increasing share of AI-driven traffic. They are also vital for ensuring high-quality service with lower latency and greater reliability. Figure 1 illustrates Nokia's spectrum vision in the 6G era, including new spectrum dedicated for 6G and re-farmed spectrum in low bands, mid-bands and high bands.

Figure 1. Nokia spectrum vision in the 6G era



Industry experience with previous mobile generations has demonstrated the necessity of dedicated launch spectrum for each new generation—such as 3G UMTS at 2.1 GHz, 4G LTE at 2.6 GHz, and 5G at 3.6 GHz. This launch spectrum is crucial, as it defines network coverage, capacity, speed and overall performance.

Joint Nokia-Telia upper 6 GHz field tests

Nokia and Telia have a long history of being early adopters in testing innovative solutions. In 2009, we launched the world's first LTE network in Gothenburg. In 2018, we conducted the world's first 5G private wireless trial in a smart factory and also carried out a 5G pre-launch at the Helsinki football stadium. Four years later, we achieved another milestone by implementing the world's first commercial network slicing service using fixed wireless access in a 5G SA network. To test the upper 6 GHz in real-world conditions, Nokia and Telia collaborated once again.

As current 5G capacity will be fully utilized in the coming years, operators will need new spectrum to meet the growing demand for additional capacity in both outdoor and indoor locations. Tests were conducted to validate the matching capabilities—in terms of coverage and performance—of concept radios operating in upper 6 GHz frequencies with commercial radios operating in today's typical 5G mid-band spectrum. The tests looked to confirm that reuse of existing live 5G outdoor site grids with mid-band radios is technically possible and yields satisfactory results.

Collaboration between Nokia and Telia enabled us to conduct the tests in real-life environments using an outdoor 3.6 GHz radio network site, a test site from Nokia, and a test license for the spectrum in the upper 6 GHz band.

Technical details

The Nokia-Telia field tests were conducted in two types of live environments: outdoor and indoor. The outdoor test measured throughput in a suburban base station site in Espoo, Finland. Indoor measurements were made at Nokia headquarters in Espoo, Finland.

The tests compared the performance of the upper 6 GHz and 3.6 GHz radios deployed on the same sites, using a test license reserved for Telia in the range 7.0–7.1 GHz of the upper 6 GHz band.

The pre-commercial concept radios and user equipment used for the upper 6 GHz band have limitations as compared to the commercial equipment used for the 3.6 GHz band, not having yet undergone full performance optimization and validation. Future standardized commercial equipment for the n104 band (6425–7125 MHz) will have significantly improved performance over current pre-commercial equipment.

Additionally, the test license limited the available channel bandwidth to 60 MHz, lower than the expected channel bandwidth of at least 200 MHz for commercial 6G deployments, also impacting performance.

Base station characteristics

Radio equipment used in the test included:

- For the upper 6 GHz range, we used a concept Massive MIMO 128 TRX radio based on the Nokia AirScale platform
- For 3.6 GHz we used a commercially available Nokia AirScale Massive MIMO 64 TRX radio
- Both radios used the Nokia Sounding Reference Signal (SRS)-based beamforming — beamforming algorithms being essential for Massive MIMO as they help extend coverage, increase throughput and boost the spectral efficiency of radio cells
- Carrier bandwidth was 60 MHz in both bands, limited by the test license conditions.

The Massive MIMO radios used in the field tests for both the upper 6 GHz and 3.6 GHz bands employed SRS-based beamforming to enhance performance. For each measurement point, a beamforming analysis was conducted to ensure that beamforming was functioning correctly in both radios. This validation was

essential to endorse the test results for the upper 6 GHz and 3.6 GHz bands. The analysis confirmed that the measurements from both bands are reliable and can be safely compared.

Additionally, as 6G aims to support wider channel bandwidths of at least 200 MHz for the upper-mid band spectrum, in line with ongoing 3GPP standardization work for 6G [4], we extrapolated test results to provide likely outcomes when using such large bandwidths in the upper 6 GHz band.

The table below provides the detailed parameters of the base stations used in the trials.

Table 1. Base station parameters in the test setup

Base station characteristics	Upper 6 GHz concept radio	3.6 GHz commercial radio
Frequency range	7000–7060 MHz	3640–3700 MHz
Bandwidth	60 MHz	60 MHz
Subcarrier spacing	30 kHz	30 kHz
Tx/Rx channel	128	64
Maximum effective isotropically radiated power (EIRP)	75 dBm Corresponds to 77.2 dBm/100 MHz with the same power spectral density (PSD)	75 dBm Corresponds to 77.2 dBm/100 MHz with the same power spectral density (PSD)
Antenna gain	30 dBi	24.5 dBi
Number of antenna elements	768	192
TDD frame structure	DDDSU	DDDSU
Antenna height (above the ground)	23 m	23 m

Test terminal characteristics

The pre-commercial test terminal (user equipment) used in the trial had integrated omni antennas supporting both the 3.6 GHz and upper 6 GHz bands and used the same key parameters for both bands.

Table 2. Test terminal parameters in the test setup

Test terminal characteristics	Upper 6 GHz	3.6 GHz
Tx/Rx channel	2Tx/4Rx	2Tx/4Rx
Max transmit power	24 dBm (250 mW)	24 dBm (250 mW)

The test terminal used the iPerf Transmission Control Protocol (TCP) tool to generate network traffic for verifying the received signal. In TCP traffic, the receiver needs to acknowledge each received data packet to the sender. For example, when the user equipment receives a TCP data packet in downlink, it sends an acknowledgement to the iPerf application server in uplink. At each of the measurement points, several iPerf TCP throughput tests were performed for both downlink and uplink to capture the main performance indicators.

Suburban outdoor-to-outdoor

Test arrangements

The outdoor-to-outdoor (O2O) test compared the performance of the concept radio operating in the upper 6 GHz band and the commercial radio operating in the 3.6 GHz band in the same suburban setting in Espoo. The two radios were collocated on the rooftop site, with the main beams pointing along a railway track. Figures 2 and 3 show details of the site location and the perimeter of the trial.

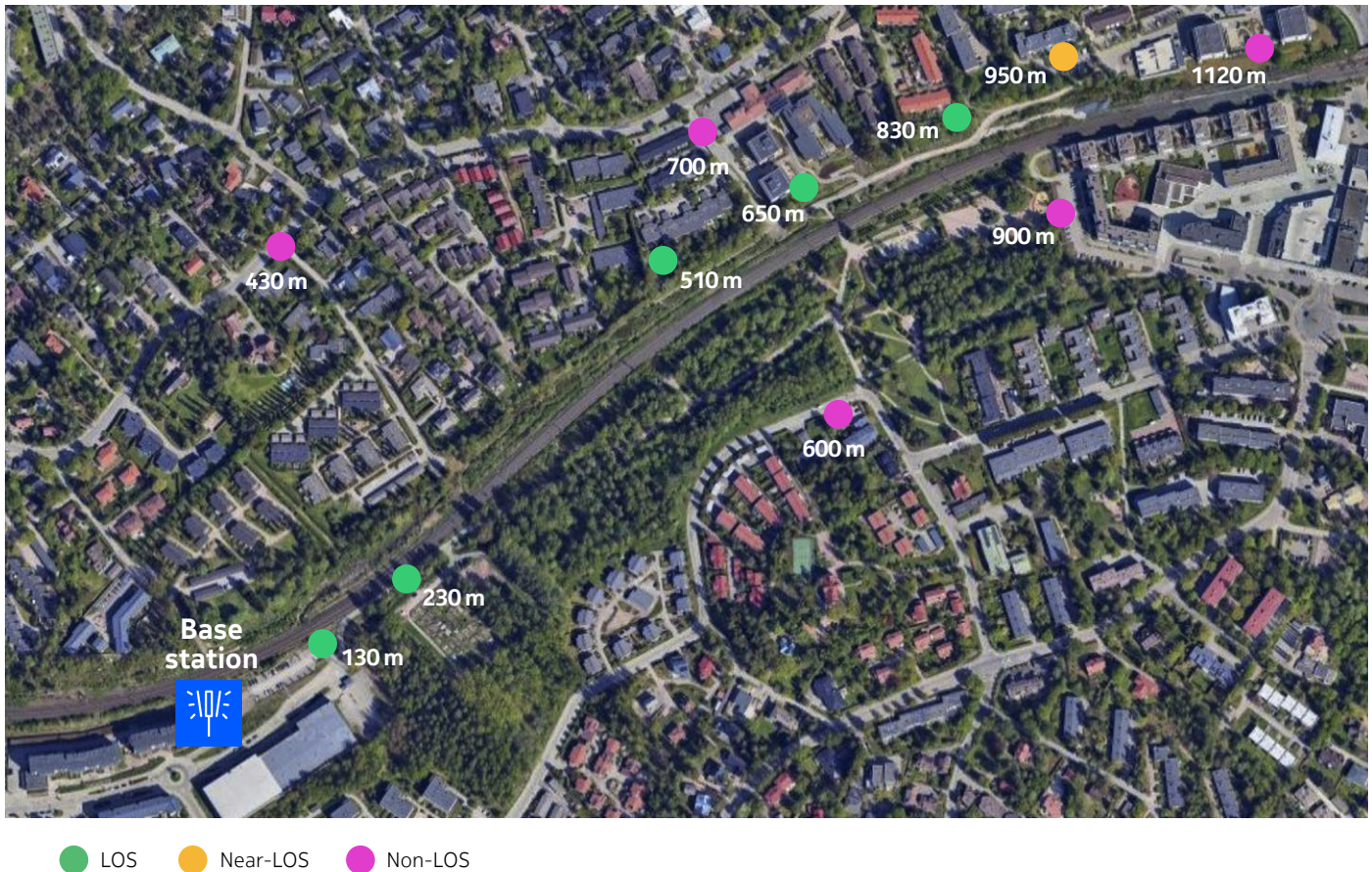
Figure 2. Suburban rooftop site with upper 6 GHz and 3.6 GHz radios



To verify the received signal, the test terminal generated network traffic using the iPerf TCP application. The received downlink signal levels were measured at distances between 130–1120 meters from the base station:

- Line-of-sight (LOS) propagation paths at distances of 130–830 m
- Non-line-of-sight (non-LOS) propagation paths at distances of 430–1120 m
- Near-line-of-sight (near-LOS) propagation path at a distance of 950 m.

Figure 3. Distance of the test terminal from the rooftop site



Field measurement results

For the stationary test runs, the test terminal was positioned outside of a van window using a mount, as shown in Figure 4. The van was parked at each of the measurement points.

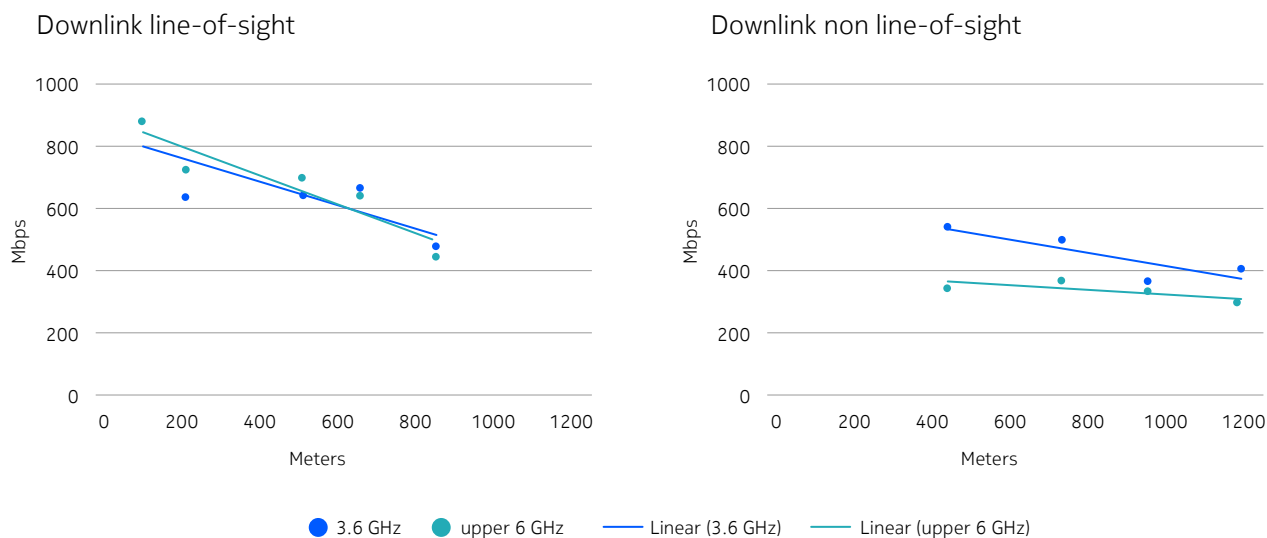
Figure 4. Test terminal position in O2O test



Average measured values for downlink throughput are illustrated in Figure 5:

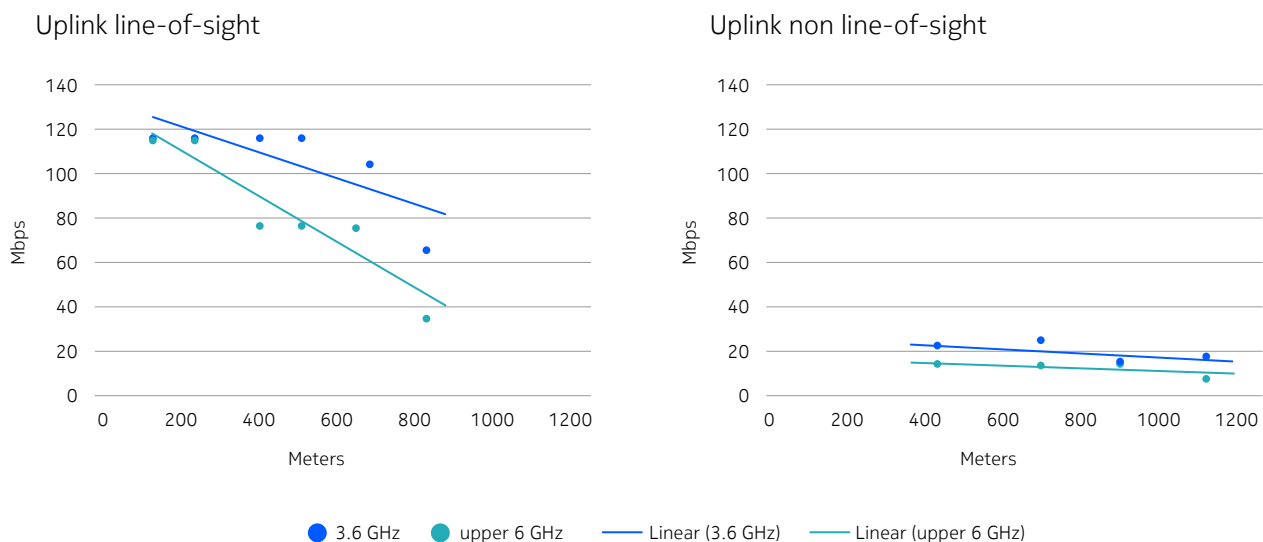
- With LOS radio conditions, the average downlink throughput was similar for both upper 6 GHz and 3.6 GHz bands
- With non-LOS radio conditions, downlink throughput measurements for the 6 GHz band were in line with expected outcomes, that is on average at 75% of the data rate of the 3.6 GHz band.

Figure 5. Downlink LOS and non-LOS test results



The average measured values for uplink throughput illustrated in Figure 6 show good results when using the upper 6 GHz spectrum, with uplink throughput in the upper 6 GHz on average at 76% of the data rate of the 3.6 GHz band with LOS radio conditions, and at 67% with non-LOS radio conditions.

Figure 6. Uplink LOS and non-LOS test results



Overall, in a standard macro set-up utilizing 60 MHz bandwidth channels with equivalent maximum EIRP of 77.2 dBm/100 MHz, field tests indicated a good level of performance for the upper 6 GHz band, aligned with the expectations, providing matching coverage and capacity with the 3.6 GHz band.

- **Coverage and capacity:** The upper 6 GHz band has shown comparable performance to the 3.6 GHz band up to 830 m from the rooftop base station antenna in an outdoor environment
- **Extended performance:** Beyond 830 m, the upper 6 GHz downlink continues to deliver good downlink performance, up to 1120 m
- **Throughput:** Tests indicated peak outdoor downlink throughputs of up to 0.93 Gbps at shorter distances.

Outdoor trials validated the capabilities of the upper 6 GHz band using Massive MIMO high power antennas to provide coverage with significant additional capacity when deployed in an existing macro-grid of the 5G network. Field tests suggest a smooth site evolution to 6G leveraging the upper 6 GHz spectrum and engaging stakeholders in the utilization of the spectrum in the 6–7 GHz range.

Outdoor-to-indoor

Test arrangements

The second field test, conducted in Nokia headquarters in Espoo, Finland, compared the indoor coverage that an outdoor macro base station operating in the upper 6 GHz band can provide in comparison with 3.6 GHz. The tests utilized identical technical conditions.

Figure 7 illustrates the location of the outdoor base station and the measurement points for the outdoor-to-indoor (O2I) tests.

An outdoor reference point at 65 m with LOS radio conditions from the base station was defined and the downlink and uplink performance of the test terminal was measured to serve as a reference.

Equally, several indoor measurement points were defined:

- First point at 80 m from the base station, right behind an infrared-reflecting (IRR) glass window
- Second point at 90 m, in a meeting room with an additional inner glass wall, compared to the first measurement point
- Third point at 100 m, a showroom in deep indoors, behind two walls and with no windows.

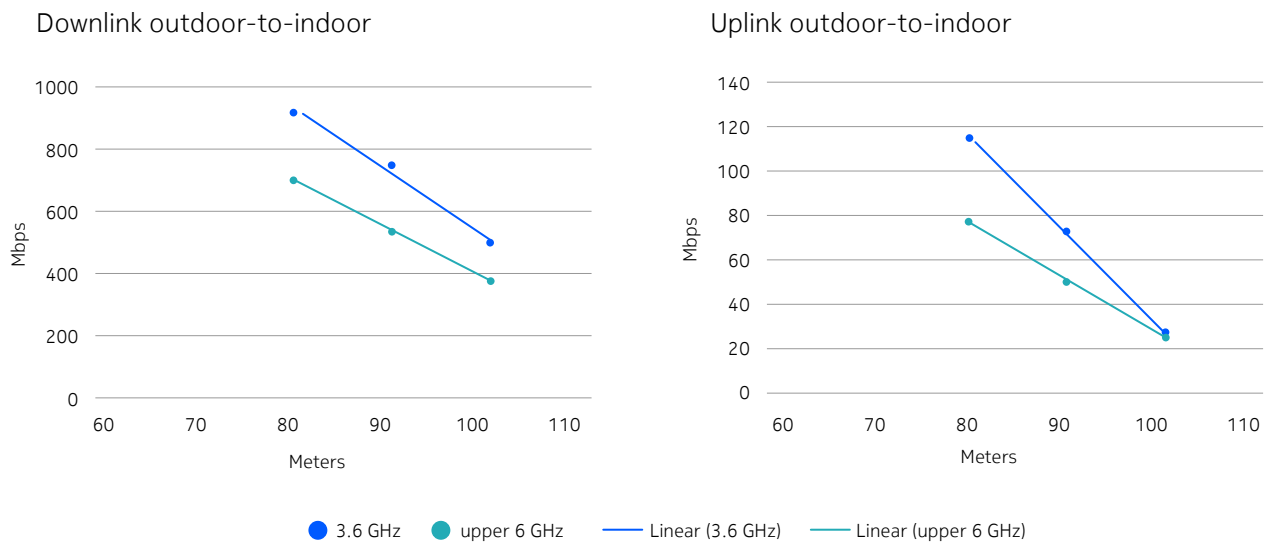
Figure 7. O2I measurement points



Field measurements results

Figure 8 shows the downlink and uplink throughput for our O2I test using the outdoor LOS point as a reference for evaluating performance.

Figure 8. O2I throughput measurements



The results show that an outdoor macro base station using the upper 6 GHz band can reliably serve indoor mobile users up to 100 meters away. While average throughput was slightly lower than the 3.6 GHz band due to the different propagation characteristics of the two bands, the 6 GHz band still achieved peak downlink throughputs of up to 0.70 Gbps in indoor conditions, along with good uplink performance. These results suggest that the 6 GHz band holds promise for providing reliable O2I capacity for mobile communications.

Summary of field measurements results

The tests performed in the two locations confirm the suitability of the upper 6 GHz band for macro-cellular outdoor deployments. The 6 GHz band demonstrated the ability to provide coverage and additional capacity to the mobile networks, effectively serving both outdoor and indoor clients.

Despite the limitations of the current test set-up—such as the parameters allowed by the test license and prototype equipment—results confirm that the upper mid-bands are a viable option to address predicted mobile traffic growth. These bands will be essential for providing additional radio network capacity and accommodating incremental data traffic.

Future commercial radio equipment for the upper 6 GHz band, using Massive MIMO antennas and larger bandwidth channels, will offer improved performance compared to prototypes. This will enable significant additional capacity in the mobile network using the existing macro-cellular infrastructure, ensuring rapid, economic and sustainable rollouts.

Field tests using the upper 6 GHz band with 60 MHz bandwidth with an equivalent maximum EIRP of 77.2 dBm/100 MHz indicate outdoor performances coverage of up to 1120 m as well as peak outdoor downlink throughputs of up to 0.93 Gbps at shorter distances. Additionally, indoor coverage tests were conducted at distances of up to 100 m, achieving peak downlink throughputs of up to 0.70 Gbps in indoor conditions, along with good uplink performance.

Significant potential for 6G networks: Extrapolation of test results for larger bandwidths

Extrapolating upper 6 GHz test results for 100 MHz bandwidth and equivalent maximum EIRP of 77.2 dBm/100 MHz, a peak throughput of over 1 Gbps can be achieved in both indoor and outdoor scenarios. Such performances would allow operators to efficiently address the additional radio capacity required in their networks, potentially before the end of the decade. However, in very deep indoor conditions, uplink performance can be maximized by relying on the 3.6 GHz range.

For the upcoming generation of mobile technology in the 2030 timeframe, Nokia considers that the successful initial introduction of 6G requires the availability of the upper 6 GHz band with a minimum of 200 MHz per operator. Any lower bandwidth would render the band less attractive and reduce its efficiency in use.

Consistent with this recommendation, normalized throughput values were calculated for 200 MHz bandwidth channels. The Massive MIMO throughput values with four downlink and two uplink layers assume a maximum EIRP of 80 dBm/200 MHz, maintaining the same power spectral density as the 60 MHz results.

Tables 4 and 5 below show the normalized throughput values with 200 MHz bandwidth in suburban O2O and O2I environments, respectively.

Table 4. Normalized throughput values for a 200 MHz bandwidth in a suburban O2O environment

Upper 6 GHz 200 MHz OBW	Outdoor distance		
	130 m	650 m	1000 m
DL MU-MIMO	3 Gbps	2.2 Gbps	1.4 Gbps
UL MU-MIMO	390 Mbps	250 Mbps	80 Mbps

Table 5. Normalized throughput values for 200 MHz bandwidth in a O2I environment

Upper 6 GHz 200 MHz OBW	Indoor distance		
	80 m, behind window	90 m, behind window + inner glass wall	100 m, deep indoor, no windows
DL MU-MIMO	2.3 Gbps	1.7 Gbps	1.2 Gbps
UL MU-MIMO	260 Mbps	170 Mbps	80 Mbps

The extrapolated values above indicate the significant advantages of using the upper 6 GHz band with 200 MHz channel bandwidth. This large bandwidth allows for similar technical conditions of power spectral density and provides three times better performance compared to 60 MHz channels in both O2O and O2I scenarios, for both uplink and downlink.

While channels of 100 MHz bandwidth may seem appealing, their net benefit compared to the same bandwidth in the 3.6 GHz range would not necessarily justify future investments. The real advantage of the upper 6 GHz band is the ability to offer larger channels of at least 200 MHz per operator. This capability is crucial for addressing the demand for high throughputs, data rates, and superior quality of service, which are essential to meet the anticipated capacity crunch in mobile networks.

Conclusions and recommendations

As we transition towards 6G, efficient provision of multi-gigabit connectivity is paramount to meeting the growing demand for higher mobile data rates and network capacity. Our testing of the upper 6 GHz spectrum for mobile broadband services, conducted using existing macro network infrastructure, has yielded promising results in both indoor and outdoor environments.

- These tests confirmed the feasibility of deploying upper 6 GHz Massive MIMO radios in urban environments, where current 5G network capacity limits will soon be reached, necessitating access to new spectrum to accommodate the increasing capacity demands.
- The field tests demonstrated comparable performance for the upper 6 GHz concept macro radio and commercial radios in the 3.6 GHz band. Future commercial radio equipment for the upper 6 GHz band using larger bandwidth channels will offer improved performance compared to pre-commercial equipment. This will enable significant additional capacity in the mobile network using the existing macro-cellular infrastructure, ensuring rapid, cost-efficient and sustainable rollouts.
- Extrapolations based on test results showed that efficient gigabit connectivity can be achieved with 200 MHz channels in upper 6 GHz, identifying this band as an effective candidate for the initial deployment of 6G on existing macro-cellular infrastructure.
- As 6G networks will feature wider carrier bandwidths and the future Massive MIMO radios will have a larger number of transceivers enabling more multi-user MIMO layers, we expect significantly higher throughput on the upper 6 GHz spectrum band in scenarios with favourable signal-to-noise (SNR) or signal-to-interference-plus-noise (SINR) ratios.
- Future technologies will also introduce optimized beamforming techniques, AI-native air interfaces, and more antennas to the user equipment supporting the upper 6 GHz spectrum. For these reasons, we expect that commercial upper 6 GHz mobile networks will perform better than the initial results presented in this white paper.

Drawing from the above conclusions, Nokia proposes three key recommendations to administrations regarding the upper 6 GHz spectrum band:

1. To address the increasing demand for higher mobile data rates and network capacity, Nokia recommends allocating 200–400 MHz of bandwidth in the upper 6 GHz spectrum band for each mobile operator by 2030, facilitating the timely introduction of 6G
2. A clear spectrum roadmap for 6G brings certainty and confidence, triggering the emergence of a solid end-to-end ecosystem and enabling the strategic planning for mobile network evolution
3. Defined timelines and harmonized licensing conditions—both technical and regulatory—encourage early planning of investments in infrastructure upgrades to address the anticipated capacity crunch.

Nokia is committed to continuously enhancing its product and technology roadmaps to enable our customers to leverage new spectrum bands as they become available and ensure a future-proof network evolution to 6G. Following the tests in Finland with Telia, we continue evaluating the upper 6 GHz band capabilities in different capital cities, exploring collaborations with operators across Europe and worldwide to address real-life conditions and evaluate challenges and opportunities. Nokia is ready to supply the demand in the band and provide equipment to ensure that upper 6 GHz can deliver critical capacity for growing data demand.

Abbreviations

DL/UL	Downlink / Uplink
EIRP	Effective Isotropically Radiated Power
IRR	Infrared Reflecting
LOS	Line of Sight
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
O2I	Outdoor to Indoor
O2O	Outdoor to Outdoor
OBW	Occupied Bandwidth
PSD	Power Spectral Density
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SRS	Sounding Reference Signal
TCP	Transmission Control Protocol
WRC	World Radio Conference

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