Extreme massive MIMO for macro cell capacity boost in 5G-Advanced and 6G

White paper

Harri Holma, Harish Viswanathan and Preben Mogensen

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Executive summary

5G-Advanced and 6G networks aim to provide advanced capabilities from new services, extreme connectivity and security to RF sensing. The future radio networks should also provide more capacity at substantially lower cost per bit and lower energy consumption. This white paper presents solutions and technology requirements for providing more capacity with the existing site grid by using more advanced massive MIMO antennas and more spectrum.

The new pioneer spectrum blocks for future cellular radios are expected to be at mid-bands 6–20 GHz for urban outdoor cells, low bands 460–694 MHz for extreme coverage and sub-THz for peak data rates exceeding 100 Gbps. Significant capacity increases can be expected using mid-band spectrum combined with extreme MIMO antenna arrays at base stations with up to 1024 elements and larger antenna arrays at the terminals. This can potentially provide around 20x more capacity compared to basic 5G in the 3.5 GHz band when using four times more spectrum per cell and achieving five times higher spectral efficiency. Such a major boost in site capacity will meet annual mobile traffic growth of 35% for 10 years without substantial site densification.

The bands that first become available in the near term can be utilized with 5G-Advanced and the bands that become available later (seven to eight years) can be used with 6G technology. These new bands will motivate 6G deployments, which will be followed by refarming of existing 5G spectrum to 6G to enhance interworking with the new 6G bands. Digital beamforming antenna gain matched to the channel can exceed 30 dBi, which helps to maintain the coverage area and to reuse existing base station sites.

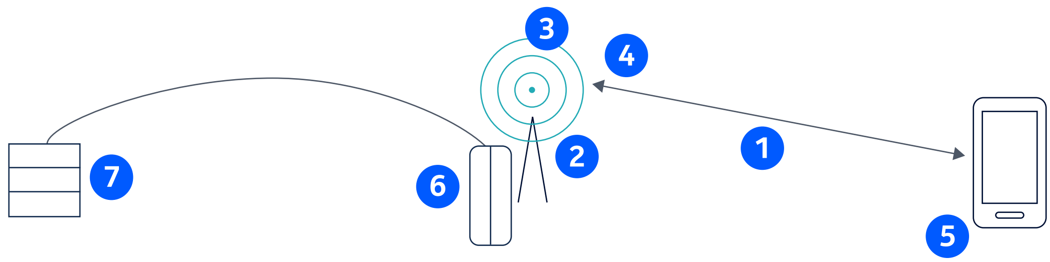
A lot of innovations will be needed to realize the extreme capacity target:

- RF front-end technology
- Scalable MIMO processing architectures
- Radio system design to benefit from the narrow beams
- Fast evolution in system on chip (SoC) processing capability
- Lower power consumption.

The 6G macro cell concept is summarized in Figure 1. Early versions of these solutions can be applied in 5G-Advanced as well.

We envision 6G radio to be highly scalable across bandwidth and array sizes. It is unlikely that the large blocks of bandwidth envisioned will be available everywhere, and all deployments will involve extreme massive MIMO. As a result, the radio architecture should be highly scalable and modular so that essentially the same basic components can be used to cost efficiently address a variety of needs from 64 TRX up to 512 TRX and 100 MHz to 400 MHz.

Figure 1. 6G wide area capacity and coverage with extreme scalable MIMO



1 - Spectrum blocks at 7 – 20 GHz and 470 – 694 MHz

2 - Artificial Intelligence Air Interface (AIAI)

3 - 1024TRX mMIMO antenna

4 - 100 Gbps peak and 20 Gbps average cell throughput

5 - Coverage by 1024AE and 32 dBi beam gain

6 - Scalable, low latency processing architectures close to RF

7 - Less delay critical radio processing in local cloud

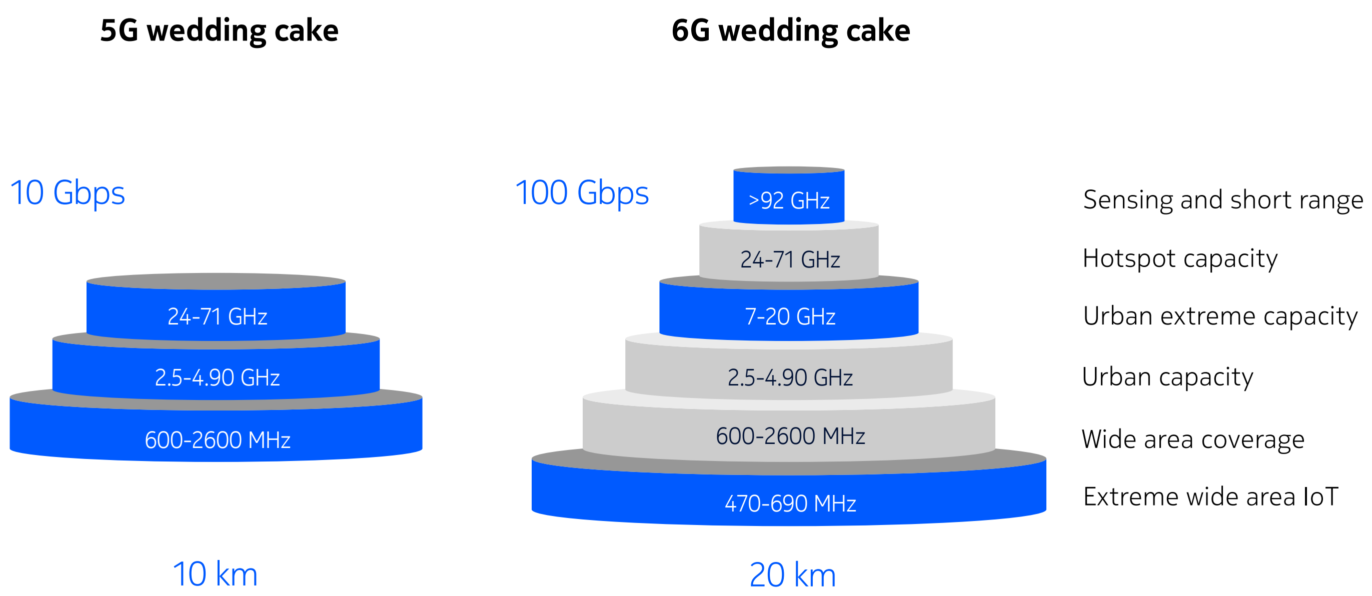
Spectrum

Spectrum is a key asset required for providing radio connectivity. Each new mobile generation requires some new spectrum to fully exploit the benefits of the new technology innovations. Refarming of the existing spectrum from the legacy to the new generation technology will enhance interworking between different spectrum blocks and minimize opex by retiring legacy networks. The same trend is expected to happen with 6G. The main new bands in 6G are expected to be as follows:

- New mid-spectrum at 7–20 GHz for urban capacity
- New low spectrum at 470–694 MHz for extreme coverage
- New THz spectrum beyond 90 GHz for the highest peak data rates and sensing.

The main new 6G bands are illustrated in a spectrum wedding cake model in Figure 2. The 7–20 GHz spectrum is the key for providing extreme wide area capacity. It allows an excellent trade-off between extreme capacity and good coverage. Extreme coverage can be provided by the by sub-1 GHz spectrum and extreme data rates by spectrum above 90 GHz. Depending on when spectrum becomes available, 5G-Advanced may first be deployed in some of these bands. The focus in this paper is on the 7–20 GHz spectrum, which will provide a strong evolution of urban macro cell capacity.

Figure 2. 6G spectrum wedding cake



Capacity

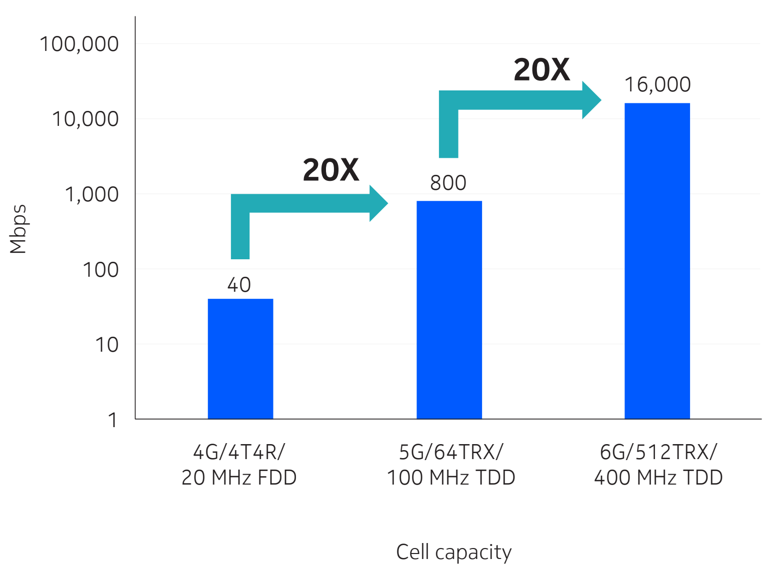
Cell capacity can be increased by using more spectrum and higher spectral efficiency systems with larger antenna arrays and new radio specifications. The same approach to mobile network evolution has continued from 2G 0.2 MHz and 3G 5 MHz to 4G 20 MHz and 5G 100 MHz component carrier bandwidth. At the same time the spectral efficiency has improved substantially mainly through use of more antenna elements: 4G uses 2x2 MIMO and 4x4 MIMO and 5G benefits from massive MIMO using up to 200 antenna elements and up to 64 TRXs.

We expect the same evolution to continue in 6G with bandwidth scaling up to 400 MHz and beyond and up to 1024 antenna elements. The target is to increase the average spectral efficiency from 10 bps/Hz to 50 bps/Hz by using very narrow beams in extreme MIMO antennas, which will allow large numbers of devices to be multiplexed in the same cell using the same time-frequency resources. The 5x increase in spectral efficiency postulated will also require larger antenna arrays at the terminals compared to 5G, which should again be possible because of the higher frequency of the new bands. 6G downlink cell capacity targets are shown in Table 1 and in Figure 3.

Table 1. Target downlink cell capacity with 6G mid-band spectrum

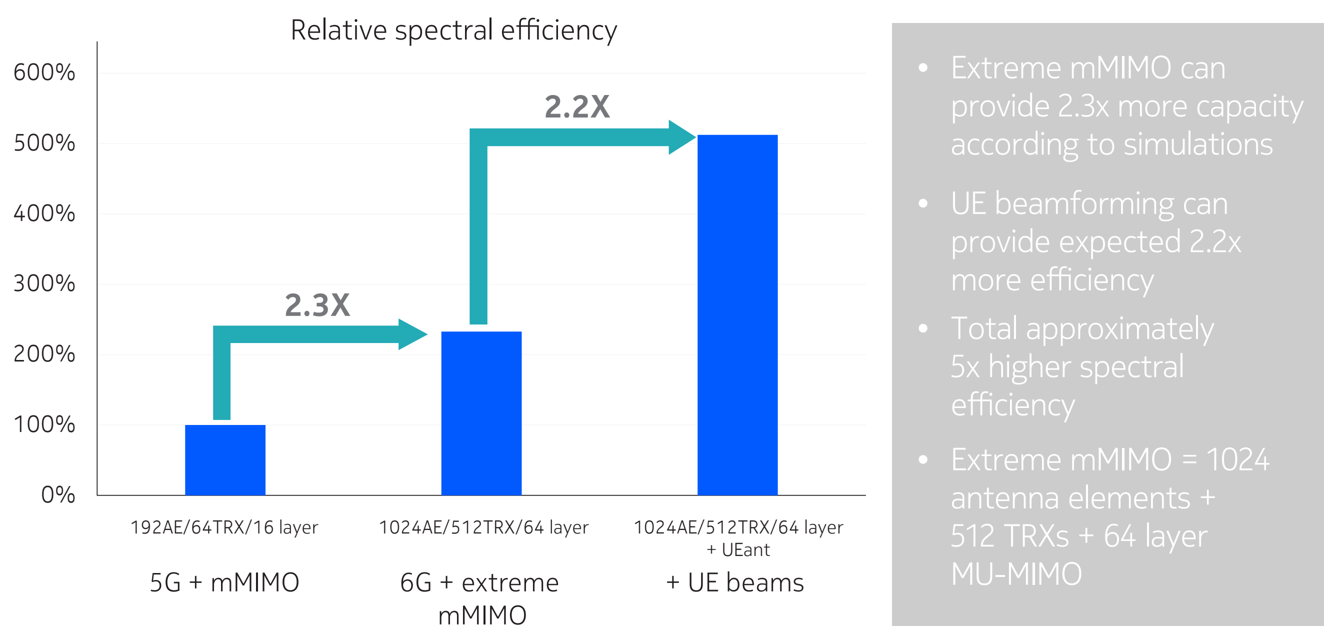
Technology	Bandwidth	Average – peak spectral efficiency	Cell capacity peak	Cell capacity average
4G	20 MHz FDD	2-20 bps/Hz	0.4 Gbps	0.04 Gbps
5G	100 MHz TDD	10-80 bps/Hz	6 Gbps	0.8 Gbps
6G target	400 MHz TDD	50-400 bps/Hz	120 Gbps	16 Gbps

Figure 3. 6G average downlink cell capacity with mid-band spectrum



As an example of one possible approach, we assumed that 6G with a 512 TRX antenna can provide 5x higher spectral efficiency compared to 5G with a 64 TRX antenna. System simulations show that the spectral efficiency can be enhanced by 2.3x when upgrading from 192 AE/64 TRX to 1024 AE/512 TRX by serving a proportionally larger number of layers simultaneously. If we want to achieve 5x higher spectral efficiency, then it is not enough. We also need to have a more advanced antenna at the UE. If we simply assume that the UE beamforming antenna doubles the spectral efficiency, we can achieve nearly the 5x target spectral efficiency gain. The relative spectral efficiency is shown in Figure 4. Also note that an actual implementation may not need 512 TRX but instead can rely on hybrid beamforming with fewer numbers of digital streams and front-end analog beamforming to achieve the same spectral efficiency. The advantage of such an approach is the reduced power consumption because of fewer numbers of converter chains.

Figure 4. 6G spectral efficiency improvements



Coverage

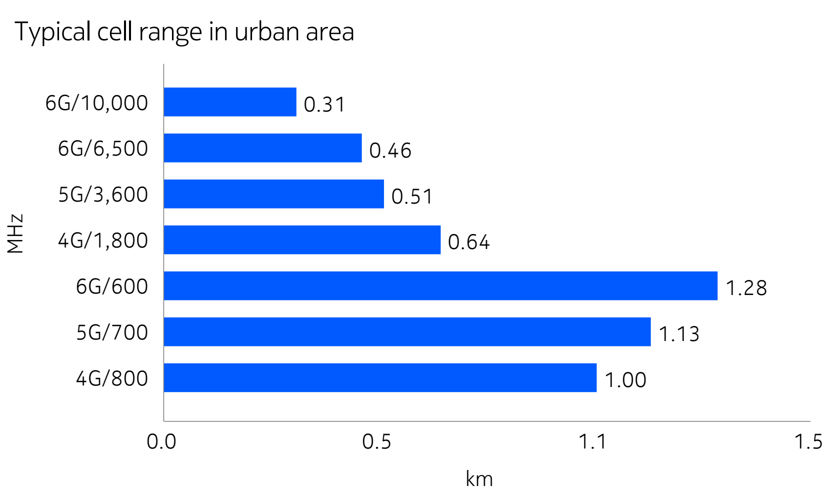
Base station sites make a large part of operator opex because of site acquisition, site rental and transport opex. Therefore, the ideal target should be to reuse existing sites to the maximum extent and to minimize the number of required new sites. The signal propagation is impacted by the transmission frequency and the cell range becomes smaller when the spectrum is higher. The loss in cell size at higher spectrum bands can be partly compensated for by higher antenna gain, which is the solution in 5G with a beamforming antenna at 3.5 GHz band. We can continue the same evolution in 6G by using a higher spectrum band with a higher gain beamforming antenna. The targets are shown in Table 2.

Table 2. Target antenna gains and required antenna elements

Technology	Spectrum	Antenna gain	Antenna element
4G	1.8 GHz	18 dBi	Passive antenna
5G	3.6 GHz	25 dBi	192 AE
6G	6.5 GHz	32 dBi	1024 AE

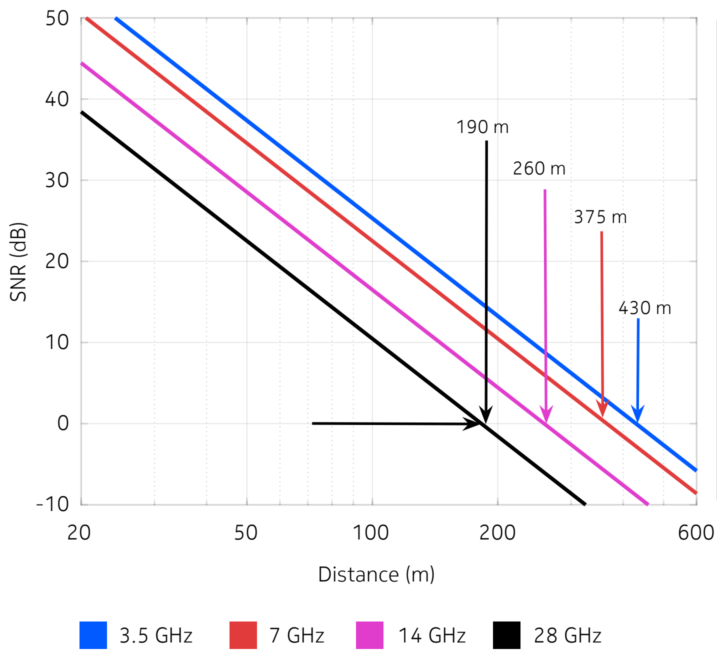
Higher antenna gain can compensate for the impact of higher path loss in theory in line-of-sight propagation conditions, but that is not the case in practice. Antenna gains as large as 32 dBi will require channel-estimation-based digital beamforming because the angle spread will be larger than the beamwidth. Typical cell ranges are shown in Figure 5 assuming the antenna gains of 18–32 dBi and assuming the Okumura-Hata propagation model. We note that 6G in mid-bands can provide nice cell ranges of 300–450 meters in urban areas, but it will not exactly match with the current LTE 1800 cell range. Therefore, low band 6G on new bands and on refarmed bands will also be required.

Figure 5. A typical urban cell range according to Okumura-Hata



Another estimate for urban cell ranges is shown in Figure 6. The path loss model is based on 3GPP studies and Nokia propagation measurements. The results show that 3.5 GHz can provide an urban cell range of 430 m while 7–14 GHz provides 260–375 m for a signal-to-noise ratio of 0 dB, which translates to 300 Mbps with 400 MHz bandwidth. These estimates show that it is feasible to use urban rooftop sites with 7–14 GHz spectrum.

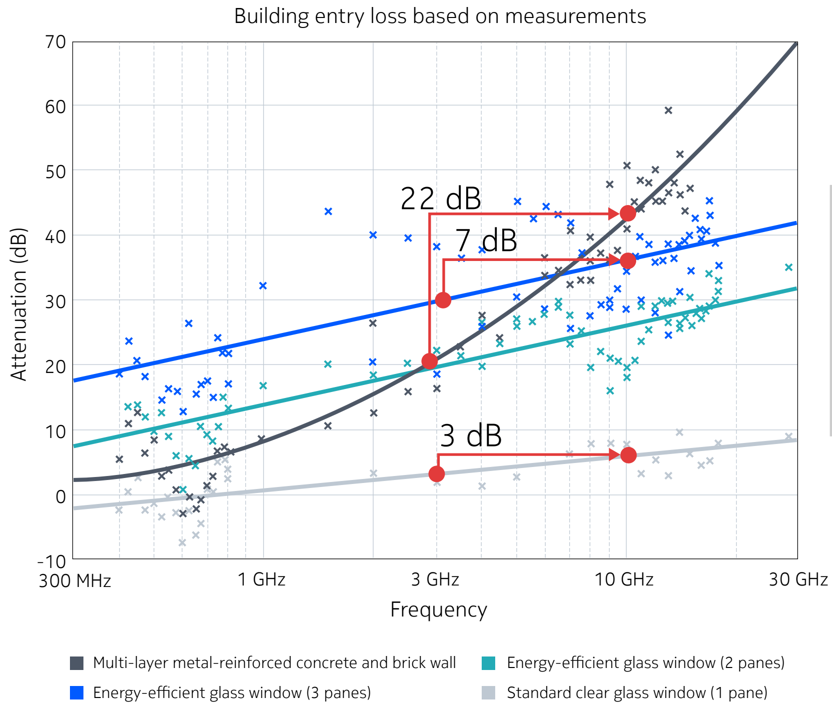
Figure 6. Urban cell range estimates for frequencies 3.5–28 GHz



- Range from rooftop to indoor is 270–375 m at 7–14 GHz providing 300 Mbps
- 400 MHz bandwidth assumed
- 200W power and 26 dBi BTS antenna limited by EIRP FCC exposure limits
- We concluded that it is feasible to use urban rooftop sites with the 7–14 GHz band

Indoor penetration creates another challenge with higher frequencies. Figure 5 assumes the same indoor penetration for all frequencies, which is optimistic since higher frequencies experience higher penetration losses. Figure 7 illustrates penetration loss measurements as a function of frequency for different building materials (the measurements were done in collaboration with Aalborg university). The penetration loss increases from 3 GHz to 10 GHz by 3 dB for clear glass and 7 dB for energy efficient glass (3 panes), which suggests that it is still possible to provide some indoor coverage by outdoor base stations at 10 GHz frequency. The reinforced concrete wall kills the outdoor-to-indoor penetration completely at the 10 GHz band and beyond. The penetration loss is 22 dB higher than at the 3 GHz band.

Figure 7. Indoor penetration loss as a function of frequency and building material



- Indoor penetration loss increases from 3 to 10 GHz
- Standard clear glass: 3 dB
- Energy efficient glass: 7 dB
- Reinforced concrete: 22 dB

The data channel coverage can be enhanced with narrow beams, but the control channels must be broadcast over the whole cell area. The control channel design in 6G must consider solutions to minimize the broadcast data rate and utilize beam sweeping solutions. Relying on very narrow beams during beam sweeping will not provide the necessary coverage if the angle spread of the channel is substantially larger than the beamwidth. Tight integration with some lower frequency band may be required for initial access, for example, using lower bands to send system information to initiate the connection through uplink transmission first that can be received through digital beamforming.

The importance of uplink data rates, capacity and coverage is expected to increase because there are industrial and consumer applications, for example, video surveillance and video sharing, that need more uplink bandwidth. In particular, new 6G use cases such as real-time mapping of physical worlds to create dynamic high-resolution digital worlds will require higher uplink capacity. The uplink coverage improvements can utilize high beamforming gain at the base station, transmit beamforming in the device, flexible TDD concepts, optimized multi-cell receptions and uplink-only sites.

Technology requirements

Major steps in technology evolution will be required to make the 6G capacity revolution practical. We list a few examples here.

Scalable RF architecture

The wide range of new mid-band spectrum with different levels of contiguous spectrum availability in different portions of the band, combined with the sub-6 GHz 5G spectrum that will be eventually refarmed for 6G, results in a diverse set of deployment bandwidths and arrays sizes. The radio design should thus cost-effectively scale for different bandwidths and antenna array sizes since it will be impractical to design many distinct radios each based on a unique set of components optimized for specific bandwidth and antenna array sizes. Radio units should instead be built in a modular way using the same basic set of component dies and flexible system-in-package (SiP) SoC and front-end modules for a range of bandwidths and array sizes. A modular approach is likely to become important for large antenna arrays and bandwidths where a radio can essentially be built by combining modular radios designed for a basic configuration.

RF front-end

The current level of technology allows us to make efficient 32–64 TRX massive MIMO antennas. The target for 6G macro cells is to increase the number of TRXs substantially, which requires a very advanced RF front-end solution in terms of size, cost and power consumption. Higher power efficiency of the power amplifier is one approach to lower cost and size.

The power consumption of up-and-down conversion and analog-to-digital and digital-to-analog conversion also scales with the number of TRXs. The current estimate for a single TRX within an mMIMO for these converter circuits is about 2W to 3W, implying very high power consumption from just these circuits when going to a very high number of TRXs. Hence, alternate approaches should be considered such as hybrid beamforming with the 1024 element antenna panel split into multiple sub-panels with a large analog beam dictionary, which will lead to fewer numbers of TRXs for the same spectral efficiency. Another power saving technique will be to reduce the resolution on the analog to digital conversion.

Another important front-end requirement is on the bandwidth. To minimize the number of front-end module variants, it is essential to have wide bandwidths while maintaining the efficiency. Finally, the interface between the integrated processing with converter SoC and the front-end module should be designed carefully so that it is straightforward to couple the processing SoC to a wide variety of front-end modules.

Artificial intelligence air interface

Higher spectral efficiency requires more advanced algorithms for the receiver processing and for the beamforming calculations. 5G mMIMO is typically designed for up to 16 layers while 6G will require up to 64 parallel MIMO layers to achieve the highest spectral efficiencies. Higher spectral efficiency can be achieved using more sophisticated receivers that jointly optimize multiple receiver blocks using, for example, deep neural networks.

By combining channel estimation together with MIMO detection, it is possible to achieve higher performance because data symbols are also automatically used in addition to pilot symbols for improving the channel estimation. Such a receiver is also essential for end-to-end learning-based systems where the transmitter constellation and pilot design are also optimized using neural networks. It is also possible that other non-linear receiver structures such as the sphere detector perform better in certain regimes and so data-driven dynamic selection of the best detection scheme can be envisioned.

Beamforming algorithms

As we go higher in spectrum within the 7–20 GHz band, it is likely that there will be a need to gradually shift to analog beamforming. Hence it is necessary to carefully consider hybrid beamforming architectures where controllable analog beamforming is seamlessly coupled with digital beamforming to achieve the highest performance at lowest cost for a given deployment environment. In hybrid beamforming, the beams are created jointly through both digital and analog combined on the same array. New algorithms that take this into account will need to be implemented. To incorporate these constraints, the best beamforming weights are produced using deep neural networks for the computation.

Since larger arrays are possible in the UE in the higher frequency range of 7–20 GHz, the combined beamforming in the network and in the UE is critical to achieve the high spectral efficiencies.

High-capacity baseband and fronthaul

Example baseband and fronthaul requirements are shown in Figure 8. The expectation is that 6G requirements will be 20x higher than in 5G due to higher bandwidth and higher spectral efficiency. The required fronthaul capacity will be approximately 500 Gbps for a 400 MHz 64-layer mMIMO antenna, which defines the optical transport requirements. Layer 1 peak cell throughput will be 100 Gbps, which defines the baseband processing requirements. If the algorithm complexity per bit increases from 5G to 6G because of the AI receiver, the required processing capability in the baseband hardware is even higher.

Figure 8. Baseband and fronthaul requirements for a 3-sector site

		5G	6G	
UE				
	Cell peak throughput	6 Gbps	100 Gbps	Layer 1 processing requirements will grow 20x
RU				
	Fronthaul requirement	25 Gbps	500 Gbps	Fronthaul requirements will grow 20x
DU	Backhaul for 3-sector	10 Gbps	100 Gbps	Backhaul requirements will grow 10x

5G = 100 MHz with 16 layer MIMO
6G = 400 MHz with 64 layer MIMO

Energy efficiency

Technology evolution alone will not provide enough power savings. Energy efficient network design will become very important by 2030 as more entities focus on meeting their aggressive climate change goals. All systems will be highly scrutinized for minimizing energy consumption. New power saving modes must be introduced at the component, node and system levels. At the component level, the digital SoC should be designed so that different portions of the SoC can be rapidly turned off and on with minimal current draw during off states. The design of the air-interface should facilitate going into such power saving modes. With processing distributed across multiple SoCs, it should be possible to flexibly allocate the processing to fewer units under less load to save power. Antenna arrays should also be flexible so that the overall power consumption is reduced under less load by switching off some TRXs. Burst mode inter-chip communication also helps reduce power consumption.

Summary

Future wide area mobile networks can deliver substantially more capacity than current 5G networks. When the deployment is largely limited to the use of existing macro sites, the main solution is new mid-band spectrum at 7–20 GHz, an extreme massive MIMO antenna and a beamforming-optimized air interface. As an example, the evolution could provide 20 times more capacity while mostly using the existing site grid in urban areas. Such a boost in the network capacity requires global collaboration to make the spectrum blocks available. We will need, as well, innovations in the underlying technology to make extreme massive MIMO feasible, including RF architecture and front-end technologies, AI-optimized beamforming, baseband processing capabilities and improved power efficiency.

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Abbreviations

AE	Antenna Element
AI	Artificial Intelligence
AIAI	Artificial Intelligence Air Interface
EIRP	Equivalent Isotropic Radiated Power
EMF	Electro Magnetic Field
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
RAN	Radio Access Network
RF	Radio Frequency
RU	Radio Unit
SiP	System in Package
SoC	System on Chip
TDD	Time Division Duplex
TRX	Transceiver
UE	User Equipment

Reference reading

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Nokia OYJ
Karakaari 7
02610 Espoo
Finland
Tel. +358 (0) 10 44 88 000

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