MediaTek 6G Technology White Paper: Sustainable Mobile Communications

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Executive Summary

Mobile communications can contribute to the United Nations Sustainable Development Goals (SDG) by offering pervasive connectivity to improve the efficiency of human society. However, it must also achieve this in a sustainable manner. Through direct and indirect incentives, these measures should stimulate the development of new technologies natively designed with carbon footprint reduction as a key objective.

Now approaching its 6G generation, mobile communications is anchored deep at the heart of our digital society, and as such uses a considerable, and increasing amount of energy to fuel the growing demand for mobile data to an increasing number of devices. Now more than ever investigations into opportunities and innovations in sustainability much be committed, which will contribute to our society's transformation towards carbon neutrality.

This white paper focuses on two directions for a sustainable 6G system design: energy efficiency and carbon-awareness. Energy efficiency ultimately aims at minimizing the overall electricity needs of the 6G system, while additionally, a MediaTek study shows that carbon-awareness could enable reducing and limiting the carbon footprint of the 6G system.

To set the foundation of our study, this white paper first reviews the latest trends in carbon neutrality regulation and investigates the possible carbon-awareness scenarios. Potential solutions for energy-efficient radio access and carbon-aware network operation are then introduced.

While MediaTek has a long relationship with the global telecoms industry and is deeply committed to standard's bodies like 3GPP. MediaTek's sustainability commitments are issued as part of its annual ESG report, and it aims to work in partnership with the industry ecosystem to promote wider sustainability objectives. The overall objective of this white paper is to inspire the development of a 6G system that is both energy-efficient and carbon-aware, enabling precise carbon footprint management and reduction, both of which are essential steps towards carbon neutrality and the sustainability of future society.

1. Introduction

The telecom sector is enabling wireless connectivity on a global scale, thereby accelerating our society's digital transformation. At the same time, the number of connected devices continues to increase, and connected applications continue to consume more data, which both lead to increased energy use [1]. To meet the Paris Agreement's climate goals, the ICT industry, therefore, ought to adopt sustainable networks and practices.

MediaTek, a global leader in smartphone platforms, communications technologies, and future-looking cellular innovations (6G), is committed to environmental responsibility, focusing on green communication networks, energy conservation in all areas of an ecosystem, and an eco-friendly supply chain. These efforts reflect MediaTek's comprehensive sustainability strategy, integral to its core values. The company aims for net-zero greenhouse gas (GHG) emissions by 2050, targeting reductions in Scope 1, 2, and 3 [2], in line with global sustainability objectives [3][4][5].

1.1. Carbon Neutrality – Kyoto Protocol and Paris Agreement

Human-induced GHG emissions from fossil fuels combined with deforestation are accelerating climate change across the globe. Unified global efforts are both urgent and essential to reduce GHG emissions, adapt to changes, and promote sustainability to protect our planet and its biodiversity. Key international frameworks like the Kyoto Protocol and Paris Agreement are instrumental in this fight.

The Kyoto Protocol [3], established in 1997 under the United Nations Framework Convention on Climate Change (UNFCCC), mandates developed nations (Annex I Parties) to reduce emissions below 1990 levels during specified commitment periods, with the inaugural period covering 2008 to 2012, aiming to stabilize atmospheric GHG levels and prevent hazardous climate impacts.

The 2015 Paris Agreement [4], building on the Kyoto Protocol, seeks to cap global warming at well below 2 degrees Celsius, with aspirations to keep it under 1.5 degrees Celsius. It introduces Nationally Determined Contributions (NDCs), where countries voluntarily outline their climate actions, fostering transparency and joint efforts to curb climate change.

Carbon neutrality has become a key strategy post-Kyoto and Paris Agreements. Net-zero emissions, in which the carbon emitted into the atmosphere and the carbon removed from the atmosphere are in balance, results from combined efforts in emissions reduction and offsetting methods like afforestation and carbon capture. All industries, including telecom, need to strive for carbon neutrality to effectively tackle climate change.

1.2. Sustainable Development Goals by United Nations

The UN's Sustainable Development Goals (SDGs) [5], established in 2015, comprise 17 goals to tackle global challenges and foster a sustainable future. The implementation of the Paris Agreement is further interconnected with specific SDGs, including sustainable cities, clean energy, climate action, and innovations as outlined below.

- Goal 7 - Affordable and Clean Energy: This goal aims to provide universal access to affordable, reliable, and modern energy, prioritizing renewable sources to cut carbon emissions.
- Goal 9 - Industry, Innovation, and Infrastructure: It targets resilient infrastructure, sustainable industrialization, and innovation, advocating for cleaner, energy-efficient technologies to lower industrial carbon emissions and advance low-carbon manufacturing.
- Goal 11 - Sustainable Cities and Communities: The focus here is on developing sustainable urban areas, enhancing public transport, and boosting building energy efficiency, which collectively reduce carbon emissions by curbing private vehicle use and promoting renewables and better waste management.
- Goal 13 - Climate Action: This goal calls for cutting GHG emissions, increasing resilience to climate hazards, and securing climate action funding. It underscores the integration of climate change into policymaking, climate education, and global cooperation to combat climate change effectively.

1.3. Emerging Carbon Neutrality Regulations for Climate Action

Studying new carbon neutrality regulations, such as carbon pricing and reporting, can potentially drive the telecom industry towards SDG 13's climate action goal. Carbon pricing, on one hand, assigns a cost to emissions, motivating businesses and individuals to switch to low-carbon options and sustainable practices. This market-based approach puts a cost on energy use, not just on data and service, and drives the shift towards sustainability. Carbon reporting regulations, on the other hand, mandate that organizations disclose their GHG emissions, enhancing transparency and accountability. These regulatory measures are instrumental in fulfilling SDG 13 objectives.

1.3.1. Examples of Carbon Reduction Through Incentive-Based Regulations

Vehicle production is energy-intensive and involves substantial raw material use, while vehicle operation predominantly burns fossil fuels. The ZEV program, pioneered by the State of California, mandates automakers to produce a set minimum number of ZEVs to meet emission targets. Exceeding these targets generates credits, which can be in turn sold, incentivizing ZEV development and aiding compliance.

Renewable Energy Certificates (RECs) are intended to enable industries to demonstrate and guarantee their use of renewable energy and, in turn, to stimulate customer adoption and generate return on these investments. Each REC represents one megawatt-hour of renewable energy added to the grid, certifying emission reductions. Organizations buy and retire RECs to offset their carbon footprint and promote renewable energy use.

The outcomes associated with ZEV credits and RECs show the potential of incentive-based regulations to gently steer industries towards innovative practices and lower emissions. Considering the widespread nature of emissions, a more widespread embrace of such regulatory measures could play a significant role in creating a global effect. Exploring analogous approaches within the ICT sector may offer advantages in the global endeavor to address climate change.

1.3.2. Carbon Pricing Strategies: Credits and Taxes

Carbon pricing is another strategy for environmental sustainability, assigning costs to carbon emissions to encourage reductions and support a low-carbon economy. Carbon credits and carbon taxes are the primary methods of carbon pricing.

Carbon credits facilitate emissions reduction by allowing the trade of emission allowances, where each allowance grants the right to emit a certain amount of GHGs. This creates a carbon market, promoting emissions cuts and cleaner technologies. There are two types of carbon markets:

- Compliance Carbon Market: This market enforces government regulations, where entities trade carbon credits to comply with emission caps. Selling surplus permits incentivizes reductions, with prices driven by supply and demand, as seen in the European Union Emissions Trading System [6].
- Voluntary Carbon Market: Here, credits are traded without a regulatory mandate. Companies and individuals buy credits voluntarily to offset emissions or support sustainability efforts. The Gold Standard [7] is a notable example, ensuring project integrity and sustainable development. This market allows entities to surpass legal requirements for carbon neutrality.

Carbon taxes are levies imposed by governments on carbon emissions to discourage and reduce fossil fuel use. For instance, the British Columbia Carbon Tax in Canada taxes fossil fuel consumption to encourage cleaner energy and efficiency. Tax revenues can fund renewable energy investments, climate mitigation, etc.

To prevent carbon neutrality setbacks, the European Union is introducing a carbon border adjustment mechanism (CBAM) to balance competition between domestic industries facing carbon pricing and those in countries without such policies. By taxing the carbon content of imports, the EU aims to prevent carbon leakage and promote fair competition and global climate action.

1.3.3. Carbon Reporting and Disclosure

Effective carbon reporting is essential for implementing carbon taxes, providing institutions/governments with a clear picture of organizational carbon footprints. Carbon reporting involves measuring, quantifying, and disclosing an organization's emissions, pinpointing emission sources, collecting data, and standardizing reports. This process helps organizations understand their impact and strategize emission reductions to meet sustainability objectives. The GHG Protocol offers a framework for classifying emissions into Scope 1, Scope 2, and Scope 3 emissions [8]:

- Scope 1 emissions: Direct emissions from sources an organization controls, such as on-site fuel combustion and company vehicles.
- Scope 2 emissions: Indirect emissions from the consumption of purchased energy like electricity, steam, or heating, produced externally but used by the organization.
- Scope 3 emissions: All other indirect emissions not under direct control, including value chain activities like emissions from procured goods and services, employee commuting, business travel, and end-user product consumption.

For example, the UK's Streamlined Energy and Carbon Reporting (SECR) framework mandates large companies to report energy use, GHG emissions (including Scope 1, Scope 2, and select Scope 3), and energy efficiency actions in their annual reports. California has also enacted climate disclosure laws requiring public carbon emissions and climate risk reporting, encompassing Scope 1, 2, and 3 emissions.

1.4. The Telecom Industry's Path to Carbon Neutrality

The telecom sector, as a major electricity consumer, should balance service provision with the pursuit of carbon neutrality. With the advent of carbon neutrality regulations, telecom companies must navigate the financial impact of carbon taxes on their energy use and operational costs, while also addressing the carbon footprint of their products and services. Carbon neutrality in telecom requires detailed carbon footprint reporting from all parties, aiming to reduce GHG emissions across the entire value chain, including users/devices, network infrastructure, data centers, and supply chains. Full engagement from all telecom industry members is essential to reach carbon neutrality goals [3][4][5].

1.4.1. Challenges for the Telecom Industry in Achieving Carbon Neutrality

The telecom industry faces distinct challenges as carbon neutrality becomes a regulatory focus:

- Telecom operators are tasked with reducing the carbon footprint of their networks. The energy consumed to operate these networks not only yields high energy bills to operators, but also additional costs incurred by the introduction of carbon taxes [9]. Thus, an incentive is provided for operators to operate networks that are not only more energy-efficient, but at the same time less carbon-emitting. A comparable situation also applies to operators of data centers, who, like telecom operators, are central to our digitized society.
- Network, device, and chip vendors should consider carbon neutrality across product lifecycles, from manufacturing to disposal. This involves minimizing energy use, optimizing energy efficiency of product operation, and extending product lifecycles.
- Users of telecom services can also influence the industry's carbon footprint by how they use the services being offered. Adopting energy-conscious practices, like powering down unused network equipment and devices, as well as using energy-efficient settings, can aid sustainability efforts.

1.4.2. Collaborative Efforts for Sustainable Next-Generation Systems

In order to comply with emerging carbon pricing and reporting regulations, stakeholders in the telecom industry will be required to measure and account for their carbon footprint in accordance with the GHG Protocol [8]. This involves analyzing both direct and indirect emissions across all scopes (Scope 1, 2, and 3) to develop effective strategies for reducing carbon emissions. Collaboration among stakeholders in mobile communication system design is crucial to achieving carbon neutrality, and this requires a close examination of emissions within the industry, including Scope 1, Scope 2, and Scope 3, to align efforts and work collectively towards the goal.

Figure 1-1 illustrates the main GHG emission sources in mobile communication systems, highlighting the energy use of networks and devices as focal points for carbon reduction in 6G systems. Telecom operators' network energy consumption is categorized under Scope 2 emissions, while network vendors account for it within Scope 3; additionally, when telecom operators sell mobile devices, the subsequent usage emissions are also part of their Scope 3. Subscribers' Scope 3 emissions include emissions from their use of communication services, and the use of communication devices contributes to both subscribers' Scope 2 and device/chip vendors' Scope 3 emissions.

The progression to 6G technology demands a concerted effort from all telecom industry players to not only reduce their operational Scope 1 and 2 emissions but also to collectively diminish total Scope 1+2+3 emissions.

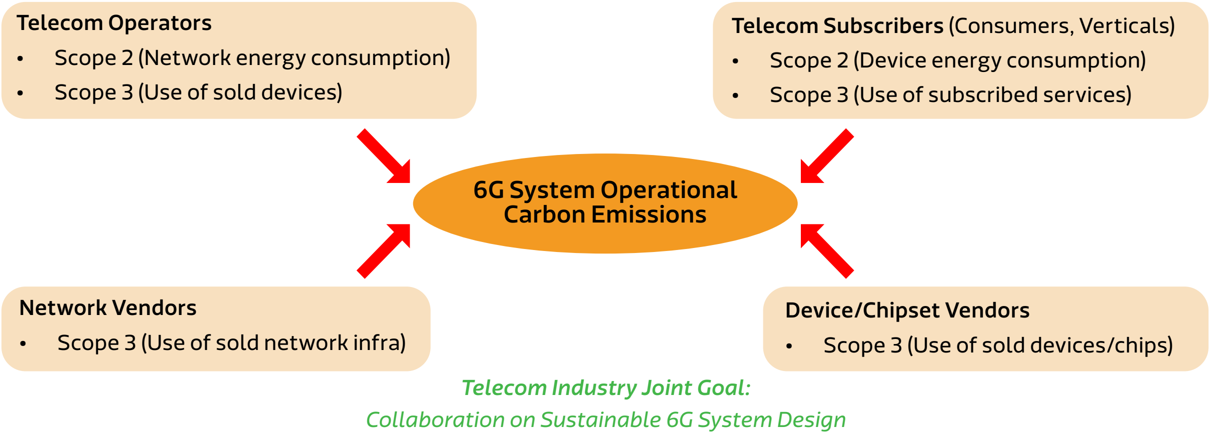

Figure 1-1: A Comprehensive View on 6G System Operational Carbon Emissions

1.5. Essential Criteria for Sustainable Mobile Networks

With mobile networks already energy-intensive, the expected around 2.5-fold data traffic surge by 2029 [10], compared with 2024, suggests a potential significant rise in energy use and carbon emissions. Achieving energy efficiency and emissions reduction is thus imperative for the telecom sector, for existing and future deployments of existing generations and is also a key focus for the development of 6G. Transitioning from 5G, 6G's sustainable deployment requires holistic planning throughout the entire system, including network infrastructure and mobile devices, and needs to be a key objective of the end-to-end design from the start.

1.5.1. Energy Efficiency Improvement

Telecom operators are increasingly concerned over the environmental impact and energy consumption of their network resulting from the increase in data demand. The imposition of carbon taxes by governments adds to the financial burden of telecom operators, particularly through electricity price increases related to carbon emissions. Towards meeting net-zero emissions goal, the telecom industry, in particular the wireless industry is motivated to enhance the energy efficiency and overall sustainability of their communication systems.

For network operators and vendors in particular, primary incentives lie in the reduction of their Scope 2 and Scope 3 emissions and in addressing rising electricity costs and carbon taxes.

For chip vendors and device vendors, core motivations are in improving user experience through better energy efficiency and in reducing Scope 3 emissions. The computational capability that can be supported within a given chip area/size has continued to increase over time. Chip power consumption trends for distinct components [11], such as active data processing-related dynamic power, remain generally stable; the foremost challenge remains improving energy efficiency for data communication to minimize the carbon footprint.

However, it is important to note that power-saving technologies, particularly over the radio interface, are typically a fine balance between device and network support and usage. For example, even if a device supports many power-saving technologies, these may not always be fully utilized depending on network support and usage. It should also be ensured that any such technology should contribute to a net sustainability improvement of the overall system – said otherwise, an improvement on a particular component should not result in a greater degradation of the performance of other components. Therefore, cooperation between device/chip vendors, network vendors, and telecom operators is essential. For 6G, considerations for joint network and device energy saving need to be incorporated from day one.

1.5.2. Carbon Awareness

Electricity is typically generated from a mix of renewable and non-renewable energy sources, such as gas, coal, and wind energy, each with varying levels of carbon emissions. Amidst efforts to curb these emissions, the shift towards renewable energy is gaining momentum. Telecom operators are at the forefront, actively increasing their use of renewables to cut down on fossil fuel dependence and shrink their carbon footprint. For example, major operators like AT&T have made significant investments in renewable energy, such as installing solar panels on their network infrastructure, to generate clean and sustainable electricity for powering their operations [12]. Carbon intensity, which measures emissions per unit of energy (e.g., gCO2 per kW·h), is an indicator of the environmental impact of network operations, where lower values represent a higher proportion of renewable energy usage.

Carbon reporting regulations act as a catalyst in fostering carbon awareness within networks operated by telecom operators, going beyond a mere understanding of a network's carbon footprint to provide valuable insights that could enable identifying and deploying efficient strategies to reduce carbon emissions reduction strategies in networks during operation. While renewable energy usage can diminish the carbon footprint of existing networks, the current lack of suitable tools for tracking and evaluating a network's carbon footprint with sufficient granularity could hinder the potential for optimization of renewable energy use.

The availability of detailed carbon intensity information within a power grid has a significant impact on the granularity of carbon awareness, particularly concerning the deployment of renewable energy. As shown in Figure 1-2, a base station with self-sustaining solar and wind power capabilities can operate independently by generating renewable electricity on-site, whereas a data center relies on a comprehensive power grid that consolidates electricity from various extensive energy sources. This means that the base station can acquire site-level carbon intensity information, while the data center receives such information at a broader regional level.

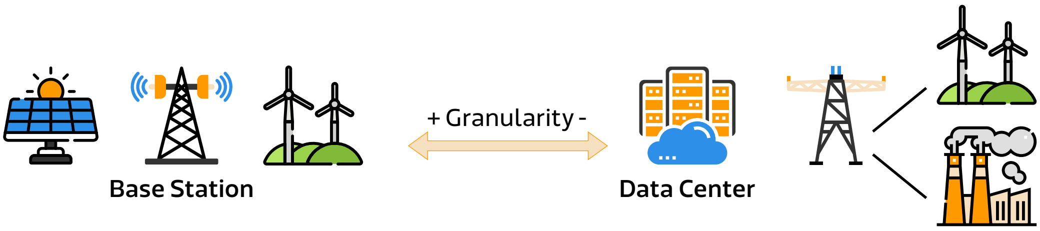

Figure 1-2: Granularity of Carbon Awareness

The carbon awareness granularity varies depending on the power grid in use. Macro grids, covering expansive geographic areas and extensive energy networks, typically exhibit a coarser level of carbon awareness due to their scale and complexity. In contrast, micro-grids display relatively finer carbon awareness granularity compared to macro-grids but coarser compared to pico-grids, while pico-grids, serving localized and smaller-scale energy distribution, demonstrate fine-grained carbon awareness with a detailed understanding of carbon emissions and renewable energy utilization at a local level. Different levels of granularity of carbon awareness can be applied by specific segments of the telecom network, depending on the geographical scale of power grids, as outlined in Table 1. In addition to spatial considerations, the granularity of the temporal dimension for carbon awareness is equally crucial. While fuel energy is consistently available, solar power is more abundant during daylight hours and wind power availability varies throughout the day and across different seasons.

Analyzing temporal granularity enables a deeper understanding of these patterns, facilitating the optimal utilization of renewable energy sources in alignment with their availability, ultimately contributing to reduced environmental impact. Such carbon intensity data facilitates coordinated optimization at various network levels, such as RAN, core network, and data centers, leading to reduced emissions through efficient matching of load and power distribution based on renewable energy availability. As detailed further in Sections 3.3 and 3.4, this allows for various degrees of carbon-aware load balancing, spatially ranging from the cell level to the task level and even up to the slice level, and temporally whenever the renewables are plentiful.

Table 1: Carbon Awareness Granularity Across Telecom Network Segments

Carbon Awareness Granularity	Power Grid Geographical Assumption	Telecom Network Segments
State/Country-level	Renewable energy sources often sparser in distribution, integrated into the grid to contribute to the overall energy supply.	Entire Network
Region/City-level	Renewable energy plants can supply electricity to a dedicated region by harnessing and storing the generated energy in storage systems.	Per Area Basis (incl. Core and/or RAN)
Site-level	Dedicated renewable energy can be directly fed into the respective facilities	Per (Hardware) Node Basis (Core, RAN)

1.5.3. Sustainable 6G

The focus of sustainable communication lies in optimizing energy efficiency and maximizing adoption of renewable energy sources [13]. This transition requires addressing design and operational aspects to reduce the carbon footprint. Key strategies for advancing 6G technology include optimizing energy efficiency, embracing diverse network conditions and topologies, and promoting carbon-awareness.

To measure the effectiveness of these strategies, the traditional Key Performance Indicator (KPI) for energy efficiency in wireless communication systems [14] is defined as the ratio of data volume (in bits) to the corresponding energy consumption (in Joules). The energy efficiency KPI (EE KPI) is expressed as:

$$\text{Energy Efficiency} = \frac{V}{EC}\ \left(\frac{\text{bits}}{\text{Joule}}\right)$$

The current EE KPI overlooks the distinction between renewable and non-renewable energy sources. To accurately assess the system's renewable energy usage and its carbon emission impact, an additional KPI is required. This KPI would measure the ratio of data volume to carbon emissions, capturing both energy efficiency and renewable energy utilization. It should also account for the fluctuating carbon intensity that varies with time and location, mirroring the specific circumstances of energy use. An example of such a KPI could be the present energy efficiency scaled by a carbon emission factor dependent on the emissions profile of the energy sources used by the wireless entity. The development of such a KPI represents an important future endeavor, preferably as a part of the standardization process, providing a quantitative measure of the system's performance in terms of energy consumption and carbon emissions, as a key aspect to support the sustainability goals discussed earlier.

Apart from the sustainable 6G development emphasized in this white paper, focusing on energy efficiency and carbon consciousness, there are several pivotal technologies advancing towards carbon neutrality. Smart grids, distributed energy storage systems, artificial intelligence, and green software stand out as critical innovations capable of optimizing energy usage and reducing carbon emissions. These technologies are vital to the smart energy ecosystem, enhancing the operational efficiency of power systems and enabling the seamless integration of renewable energy sources, thus steering us towards a greener and more sustainable future.

2. Energy-efficient Radio Access

To optimize energy efficiency, as part of the key strategies for sustainable 6G, both the data volume and the energy consumption need to be optimized jointly. This is where the technologies introduced in Section 2.1 and 2.2 come into play. In Section 2.1, a low-power radio layer design is introduced for minimization of energy consumption in idle scenarios, while maintaining coverage and mobility performance requirements. In Section 2.2, a high-efficiency radio layer is introduced for optimization of energy efficiency during data transmission/reception scenarios. Section 2.2.3 further delves deeper into the collaboration between the two radio layers, uncovering the potential for further enhancements in system performance. By combining these techniques, we can support 6G sustainability through optimized energy efficiency for any data activity or inactivity scenarios. This approach not only supports sustainability but also delivers superior connectivity performance compared to 5G.

2.1. Minimization of Energy Consumption for Idle Scenario

The lean-carrier design is a fundamental principle of NR systems, setting itself apart from LTE by eliminating the "always-on" reference signal and incorporating a Synchronization Signal/PBCH Block (SSB) with a 20-ms periodicity for synchronization, cell measurements, and broadcast information. This design modification reduces interference levels and enhances system forward compatibility when compared to 4G. The 20-ms periodicity of SSB transmission provides the lower energy consumption boundary on the radio interface at the base station (BS), including during long data inactivity periods, as illustrated in Figure 2-1 (a). This periodicity results from a trade-off to ensure good device/user-equipment (UE) mobility performance in particular. Striking a balance between further reducing energy consumption at BS side and sustaining device/user-equipment (UE) mobility performance in response to the limited resources for UE to monitor the quality of serving and neighbor cells remains a challenge.

Idle scenario power-saving is achieved through the Discontinuous Reception (DRX) technique, which allows UE to perform synchronization, cell measurement, and paging monitoring within short time durations during a DRX cycle [15]. The primary factor affecting a UE's sleep power consumption is the leakage current that occurs during sleep durations, as shown in Figure 2-1 (b). Minimizing the receiver area results in reducing the UE power consumption in idle scenario. Thus, the development of a lightweight receiver capable of handling idle mode operations can be a major contributor in saving UE power in periods of no data activity.

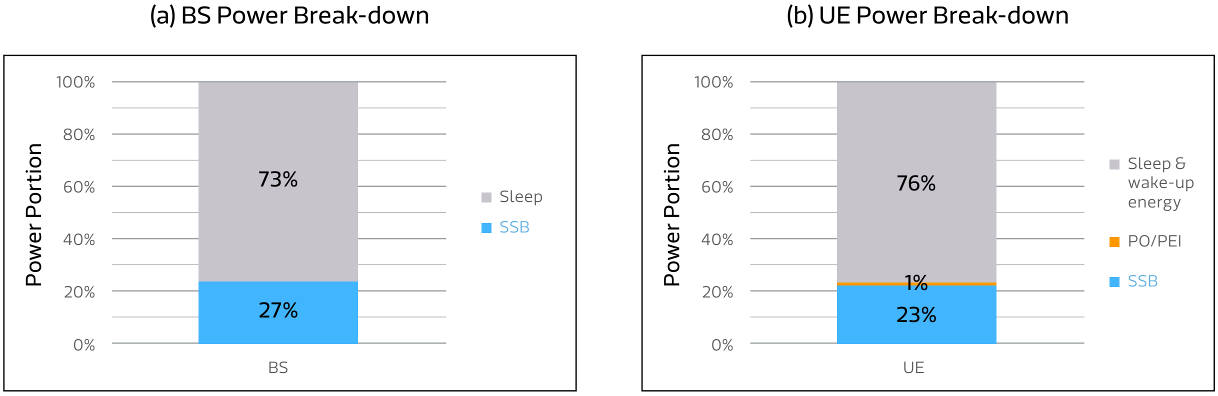

Figure 2-1: (a) BS power consumption break-down for the scenario without data traffic (b) UE power consumption break-down with DRX (1.28-second cycle) for idle scenario

An effective strategy for minimizing BS transmission power consumption involves switching off all frequency bands, sites, radio access technologies, and hardware that are unnecessary to provide minimum acceptable capacity and coverage at any given time. For mid-band deployments, reducing the antenna element (AE) number used in the 6G common signal design leads to decreased BS transmission and sleep power consumption according to the BS power consumption model developed in [16], as illustrated in Figure 2-2. The need to maintain some SSB transmission for dynamic load scenarios that require rapidly activating mid-band NR is important to consider. Compared with the legacy solution utilizing a large AE number for directional beamforming, a new common signal design can instead use the beam-sweeping occasions to carry one or multiple repetitions so that the UE can accumulate and observe a similar power level as with a directional beam by the legacy solution. By utilizing a smaller number of antennas, such a common signal design offers a more energy-efficient solution.

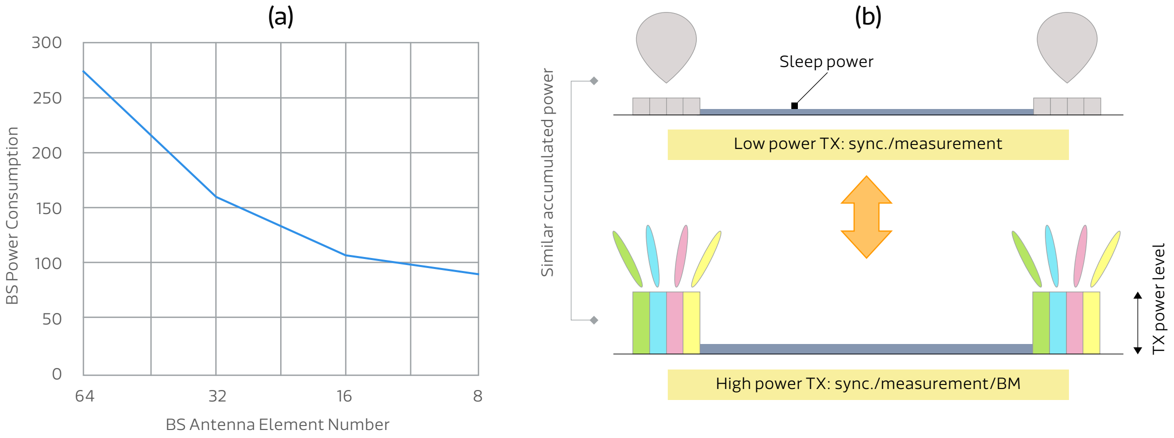

Figure 2-2: (a) Active BS transmission power consumption with different AE number and (b) Comparison of common signal transmission schemes with large and small AE number

An example of such a common signal transmission scheme is evaluated in Table 2 by comparing power consumption values for common signal transmission and micro sleep in a slot based on the BS power model in [16]. With a reduced AE number (down to 1/2 in the example), power consumption values decrease significantly. Figure 2-3 (a) demonstrates a 48% BS energy saving with the significantly reduced AE number for scenarios without data traffic.

Table 2: Power consumption values for different common signal transmission schemes; power model based on [16]

Power State	TX with large #antenna	TX with small #antenna
Common signal transmission	60	40
Micro sleep	55	28
Light sleep	25	13

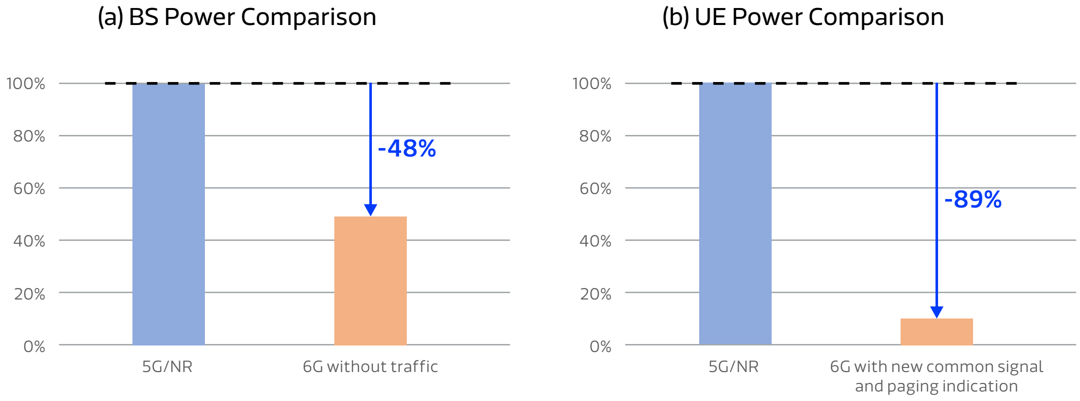

Figure 2 3: (a) BS power saving benefit with reduced AE transmission for 6G common signal and (b) UE power saving benefit with 6G low power radio layer integrating 6G common signal and paging indication

The aforementioned common signal transmission scheme can be further combined with a special signal design – low power common signal – to enable an ultra-low-complexity/light receiver at the UE side, resulting in significant power consumption reduction for both BS and UE. A potential approach for this low-power common signal is to utilize time-domain and/or frequency-domain ON-OFF keying design, enabling lightweight receiver processing with low-complexity clock generation, synchronization, and demodulation. This can reduce receiver power consumption from hundred(s) of mW to ten(s) of mW or below, leading to considerable energy savings during idle scenarios.

Additionally, such a low-power radio layer integrating low-power common signal and paging indication designs enables a UE to rely on a lite receiver to perform all necessary idle-mode operations, allowing for near-zero power consumption during idle scenarios. This can deliver more than 80% power-saving gain compared to a legacy UE utilizing a single higher-power-consumption receiver for measurement, synchronization, and paging monitoring throughout the DRX cycle. This technology extends UE battery life and enables the possibility to achieve zero carbon emissions via clean energy charging during idle scenarios. The reduction of emissions in both BS and UE sides via the introduced technology is accounted under Scope 2 of operators/subscribers and Scope 3 of network/device/chip vendors.

2.2. Optimization of Energy Efficiency for Data Transmission/Reception

Improving energy efficiency for data transmission and reception in 6G networks requires the development of a high-efficiency radio layer that incorporates novel waveform designs and energy-efficient beamforming techniques as described in Sections 2.2.1 and 2.2.2. Section 2.2.3 outlines the collaboration between high-efficiency and low-power radio layers to further optimize energy efficiency.

2.2.1. New Waveform Design

In NR, CP-OFDM is used as a major waveform to carry both uplink and downlink signals. For coverage extension, NR also supports DFT-s-OFDM in uplink transmission. These waveforms enjoy great success in both LTE and NR due to their flexibility in resource allocation and simplicity in receiver design. Moving onwards to 6G, these waveforms will continue playing key roles in supporting many critical usage scenarios, particularly for those which require extremely high throughput.

CP-OFDM and DFT-s-OFDM, widely used in 5G networks, have distinct characteristics in terms of energy efficiency. DFT-s-OFDM, in particular, is designed to offer a lower peak to average power ratio (PAPR) compared to CP-OFDM, making it more suitable for cell edge operations where power efficiency is crucial. While these waveforms are foundational to 5G, ongoing research aims to enhance their power efficiency. This includes exploring advanced techniques that allow for closer operation to the Power Amplifier's (PA) saturation point, where power efficiency is maximized, without incurring significant signal distortion or violating emission standards. To further address the energy efficiency challenges, especially in scenarios where spectral efficiency requirements are relaxed, additional candidate waveforms should be further investigated for potential integration. These advancements are key for better energy efficiency at the device side, for expanding cell coverage, and for reducing base station energy consumption. These benefits are essential for the sustainability of future 6G networks and for meeting the stringent power requirements of millimeter wave and sub-THz communications.

A low PAPR waveform would allow the PA to operate near saturation with minimum performance and spectral impacts and is therefore suitable for scenarios that require optimized energy efficiency. In fact, these waveforms have a long history and are already being used in many classical and modern communication systems. For example, constant envelope waveforms (e.g., CPM[1]) and single carrier waveforms with trajectory constrained modulations (e.g., OQPSK[2]) are both families of low PAPR waveforms that find their applications in terrestrial and satellite communication links. In addition to having low PAPR, to support 6G usage scenarios, it is important that the waveform maintains its capability in supporting flexible time-frequency resource allocations. Simplicity and manageable complexity in receiver architecture are also critical, particularly for broadband applications. To satisfy these requirements, many advanced 6G waveform candidates have been developed, including CPM-SC-FDMA[3], 1+D pre-coded DFT-s-OFDM with $\pi/2$-BPSK modulation, and TC-DFT-s-OFDM[4]. These new waveform designs can be viewed as a combination of traditional low PAPR waveforms and CP-OFDM and could all provide noticeable PAPR improvements without sacrificing their flexibility in resource allocation and simplicity in receiver design, particularly in the low spectral efficiency region. As an example, Figure 2-4 shows the PAPR improvements of TC-DFT-s-OFDM over CP-OFDM and DFT-s-OFDM for various spectral efficiencies.

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[1] Continuous phase modulation

[2] Offset quadrature phase shift keying

[3] Continuous phase modulated SC-FDMA [17]

[4] Trellis coded DFT-s-OFDM [18]

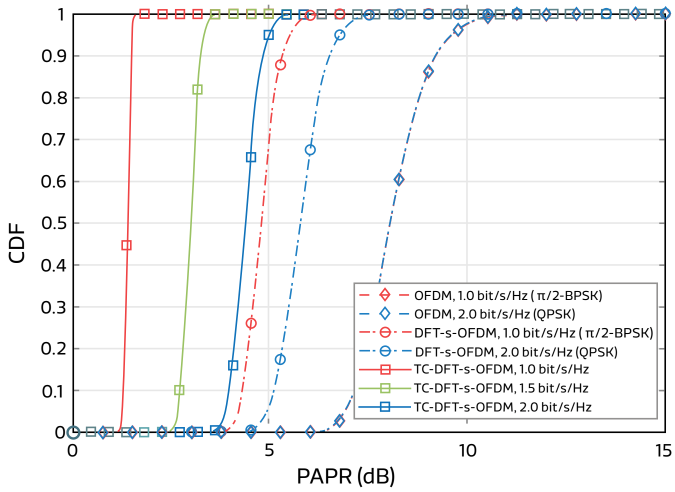

Figure 2-4: PAPR distributions of various 6G waveform candidates

The new waveforms discussed above certainly would help improve energy efficiency in use cases such as cell coverage extension, sub-THz communications, and low power IoT networks. However, for other use cases (e.g., scenarios requiring high spectral efficiency or MIMO), CP-OFDM or DFT-s-OFDM may still be preferred in terms of trade-offs between performance, receiver complexity, and energy consumption. Finding a way to efficiently integrate and operate these new and legacy waveforms to ensure the best possible balance between spectral and power efficiency for each possible scenario has become a new challenge and priority in 6G waveform design.

2.2.2. Energy-efficient Beamforming Design

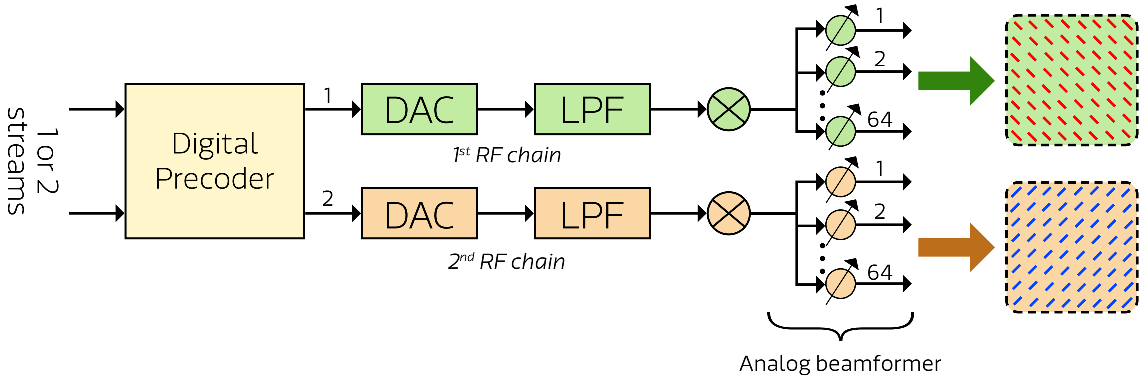

Figure 2-5: Architecture of a hybrid beamformer with 2 RF chains

Hybrid beamformers are prevalent multi-antenna transceivers for reducing hardware costs and training overhead in massive MIMO systems. In particular, at high carrier frequencies such as mmWave and sub-THz, the beamforming gains provided by large antenna arrays are crucial for compensating for high propagation losses. Despite their popularity, some issues have been identified with hybrid beamformers (as in the architecture illustrated in Figure 2-5), including high power consumption due to numerous RF amplifiers and power amplifiers, limitations of the number of RF chains on data stream support, and restrictions on data rate by the accuracy of analog beamforming.

To enhance network energy efficiency, 6G communications should focus on more energy-efficient beamforming design directions. One critical paradigm shift is the evolution from hybrid beamforming towards an all-digital beamforming architecture (with a large number of digitized RF chains) for both BS and UE, offering several benefits such as supporting higher data rates, spectral efficiency, energy efficiency, and modularization of subarrays for power scalability according to cell traffic demands.

In 6G, hybrid beamforming is expected to use more RF chains to harness the high spatial multiplexing gains of MIMO schemes. Using more RF chains results in higher data rates and spectral efficiency due to the increased degrees of freedom. However, power consumption may rise due to the addition of power-consuming components such as RF amplifiers, power amplifiers, and ADC/DACs. It is anticipated that all-digital beamforming incorporating lower-resolution DACs/ADCs at the BS will be widely adopted.

System-level simulations (Figure 2-6) indicate the benefit of using more RF chains at BS for higher average spectral efficiency in a cell with the same power consumption. This data suggests that an architecture utilizing all-digital beamforming is energy-efficient, with system spectral efficiency increasing alongside the number of RF chains when the system consumes the same total power.

Another approach involves BS beamforming supporting MU-MIMO transmissions at mmWave or Sub-THz bands, assisted by more RF chains. Performing beamforming for MU-MIMO schemes at these bands may require advanced beam management mechanisms, presenting an opportunity to enhance the spectral efficiency of cells. Figure 2-6 shows that the MU-MIMO scheme is more energy-efficient for cells than the SU-MIMO scheme under the same system power consumption.

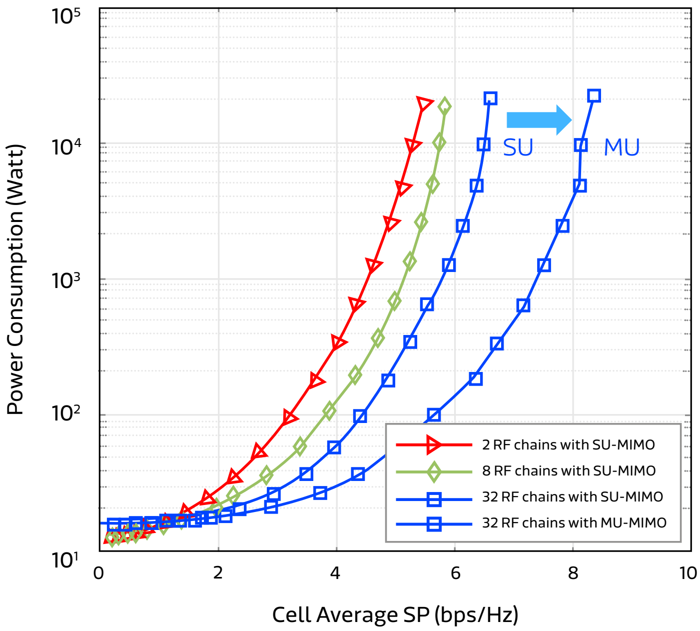

Figure 2-6: Spectral efficiency enhancement using various numbers of RF chains at the BS (with only up to two data streams per user)

In addition, adaptable RF chain switching on and off at mmWave or THz bands allows the cell to achieve high energy efficiency. Each RF chain can be connected to a modularized subarray performing individual analog beamforming, as illustrated in Figure 2-7. Adaptive on-off switching of RF chains allows for tailored energy consumption depending on the required spectral efficiency (SE), as shown in Figure 2-8. Given a requirement of SE, switching on the most appropriate number of RF chains can save power for the BS. For instance, if the cell demands an SE of around 2 bps/Hz, switching on 16 RF chains will be the most energy-efficient choice. Adaptive on-off switching also has the advantage of using fewer reference signals.

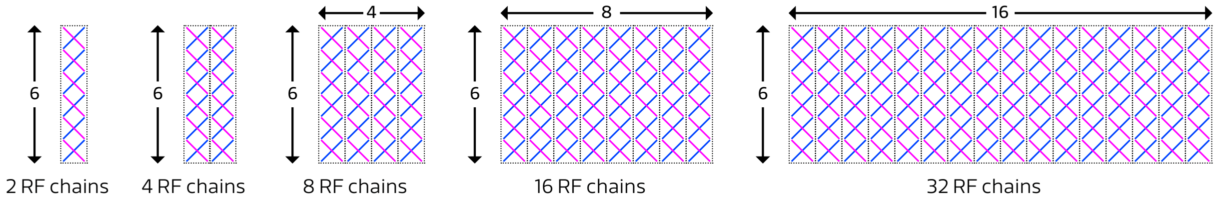

Figure 2-7: Beamformers have the structure of modularized subarrays and different numbers of RF chains

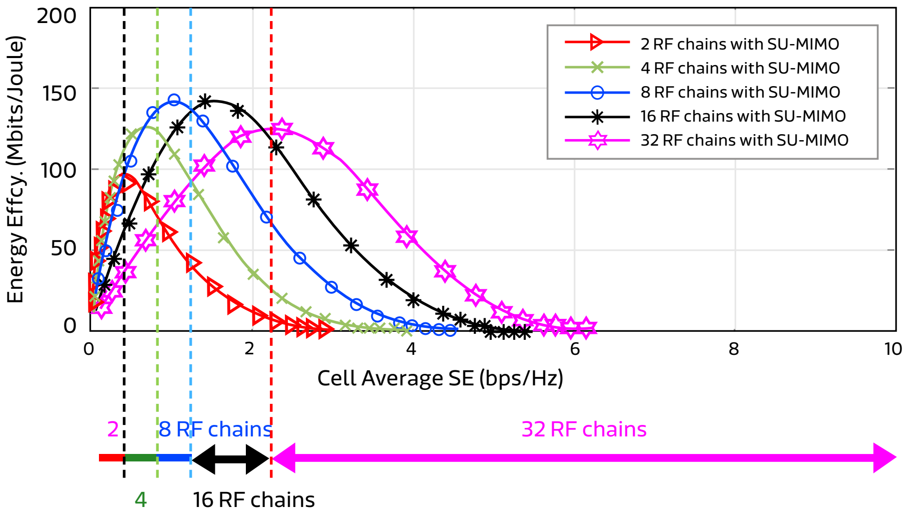

Figure 2-8: Spectral efficiency enhancement using various numbers of RF chains at the BSv

With these innovative design directions, 6G systems can pave the way for energy-efficient beamforming technologies, addressing key challenges and maximizing the potential of next-generation wireless networking.

2.2.3. Collaboration between High-efficiency and Low-power Radio Layers

Discontinuous Reception (DRX) is a widely used UE power-saving technique, resulting in a trade-off between data delivery latency and UE power consumption. This trade-off stems from the intrinsic limitation of single radio operation because a UE cannot achieve power saving and continuous monitoring of control channels simultaneously. Another limitation of single radio operation is the necessity of measurement gaps to permit RF retuning for inter-frequency measurements, which also increases data latency. To enhance data delivery performance, the low-power radio layer can be incorporated to enable monitoring data-scheduling indications and inter-frequency measurements based on near-zero-power lite receiver(s) in data transmission/reception scenarios.

The trade-off between data delivery latency and UE power consumption can be improved by having the low-power radio layer provide indications for data scheduling. By enabling monitoring of the indications at fine time granularity with a near-zero-power lite receiver, both reduced data latency and reduced UE power consumption can be realized, as illustrated in Figure 2-9. In a scenario with a 30 Mbps XR DL traffic [19], data latency can be reduced by 14% with UE power consumption also reduced by 23%.

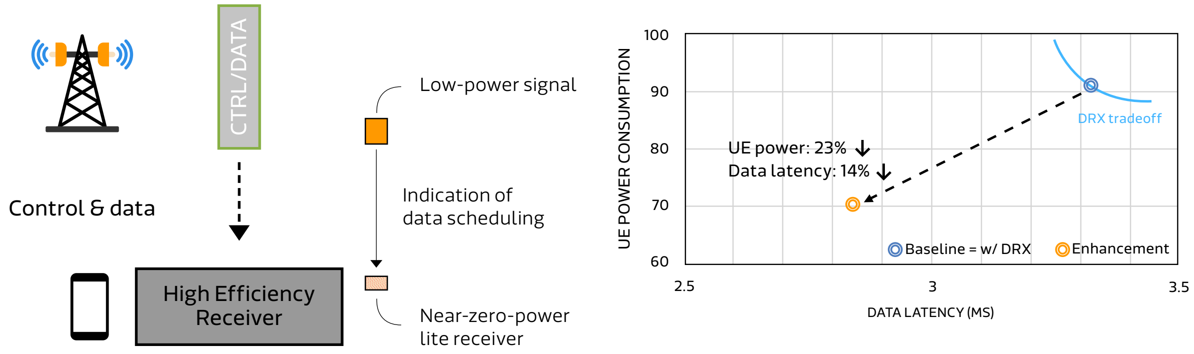

Figure 2-9. Utilization of Low-power radio layer for DRX-less scheduling and better power-latency trade-off

Furthermore, the low-power radio layer can eliminate the need for measurement gaps. As depicted in Figure 2-10 (left part), the UE can continue data reception while measuring the low power common signal from an inter-frequency neighboring cell with the near-zero-power lite receiver. Eliminating measurement gaps enhances system capacity, especially for latency-sensitive services. As demonstrated in Figure 2-10 (right part), incorporating the low-power radio layer for neighbor cell measurements contributes to 80% and 40% system capacity gains for XR services [19], with larger performance gains observed for shorter measurement gap periods in the legacy settings.

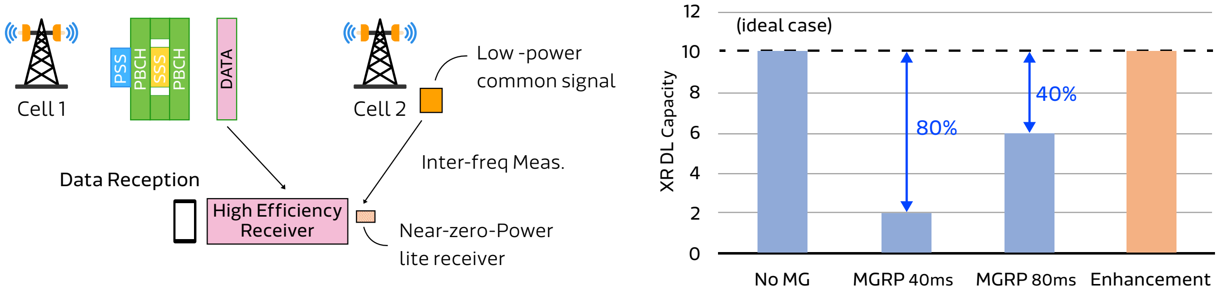

Figure 2-10: Utilization of Low-power radio layer for gap-less measurement and improved system capacity

In conclusion, collaboration of the low-power and high-efficiency radio layers shows improvement in data delivery performance and system capacity, which helps improve system energy efficiency and reduce the Scope 2 emissions of operators/subscribers and the Scope 3 emissions of network/device/chip vendors. Striving for carbon-neutrality, the focus of the next section will be on maximizing overall renewable energy utilization for a more sustainable system.

3. Carbon-Aware Network Operation

Under the pressure of carbon neutrality regulations for a sustainable future, enabling optimized operation for carbon emission reduction is crucial for telecom operators, especially with the advent of 6G, to align their network operations with a reduced environmental impact. Complementing high energy efficiency, carbon-awareness can help in monitoring and tracking the use of renewable energy at varying granularity in the system during operation and help reduce carbon emissions.

3.1. Bridging the Sustainability Gap

From a sustainable and operational standpoint, the success of 6G networks relies not only on significant improvements in energy efficiency but also on being carbon-aware, with the current 5G design providing a solid base that can be further enhanced to better evaluate a system's carbon footprint across network entities during operation. To reduce the carbon footprint, it is imperative to gain a comprehensive understanding and quantification of this carbon footprint. This entails gathering data on energy consumption and usage, including the utilization of renewable energy sources. There are some key goals to be achieved in the development of a more carbon-aware 6G system.

A first goal is the development of mechanisms to measure and report the carbon footprint of the end-to-end system in a timely manner. Developing mechanisms that can accurately monitor and track carbon emissions from different network components, including base stations, core networks, and data centers, enables operators to assess their carbon impact more effectively and identify specific areas where improvements can be made.

A second goal is to empower operators with the capability to make carbon-aware decisions based on information related to energy efficiency and carbon emissions. The integration of this information with predictive analytics allows operators to make informed decisions to optimize energy usage and maximize the utilization of renewable energy sources.

A third goal is the development of relevant KPI(s) such as that described in Section 1.5.3. Understanding the relationship between carbon emissions and diverse types of energy sources, such as renewables and non-renewables, is crucial for evaluating the carbon footprint of network operations accurately. These valuable insights brought by such a KPI guide efforts to reduce carbon emissions in network operations.

3.2. Carbon Intensity – Time and Location Dependent Profile

Electricity generation encompasses a diverse range of energy sources including renewables and non-renewables, each with its own carbon emissions profile. However, renewable energy can exhibit a degree of variability and uncertainty, especially if weather dependent, e.g., the availability of solar power depends on the time of day, wind power depends on there being wind, etc. This variability, especially without suitable energy storage, introduces challenges for operators aiming to leverage such renewables to reduce carbon emissions.

Accurate quantification of a system's carbon footprint relies on considering the carbon intensity (or emission factor) of its energy sources, representing the average carbon emissions produced per unit of energy consumed. As mentioned in Section 1.5.2, this factor varies significantly depending on the time and location, especially concerning renewable energy sources. Weather conditions, time of day, and geographical location heavily influence the availability of renewable energy, subsequently affecting the carbon intensity of the power grid. Lower carbon intensity indicates a higher abundance of renewable energy.

Gathering information on carbon intensity allows an accurate determination of the resulting carbon footprint of a system. It is expected that operations of existing networks can potentially be improved to better exploit the carbon intensity information. Furthermore, the 6G system needs to be aligned with the advancements in power grid and smart grid technologies, which are essential for acquiring carbon intensity data. To minimize carbon emissions in the presence of the fluctuating nature of renewable energy sources, it is necessary to carefully consider and monitor the carbon intensity.

3.3. Carbon-Aware System

Emphasizing the adoption and optimal utilization of renewable energy sources is necessary for reducing carbon emissions. Telecom operators can make informed decisions about energy usage by considering the fluctuations in renewable energy availability across their networks. The strategy of prioritizing operation on nodes with a lower carbon footprint, based on energy supply, encourages a careful consideration to dynamically allocate network load, which can lead to substantial reductions in emissions.

Carbon-aware load balancing becomes an essential operational tactic, involving preferentially selecting network equipment or nodes with potentially smaller carbon footprints for task execution or service provisioning, as long as acceptable performance criteria are met, e.g., when two nodes are capable of handling the same task and available, the one powered by greener energy would be prioritized. This decision-making process not only reduces the carbon footprint but also maintains the performance of the network services. In the core network, where nodes often operate in pools, operators can apply policies that prioritize nodes with lower carbon intensity within these pools. When the carbon intensity information is available and synchronous in the access network, a new mechanism can be developed to allow the UE to identify and select a cell utilizing more renewable energy, as illustrated in Figure 3-1. Such a mechanism that shifts communication load towards reducing network carbon emissions is an interesting concept that merits additional investigation.

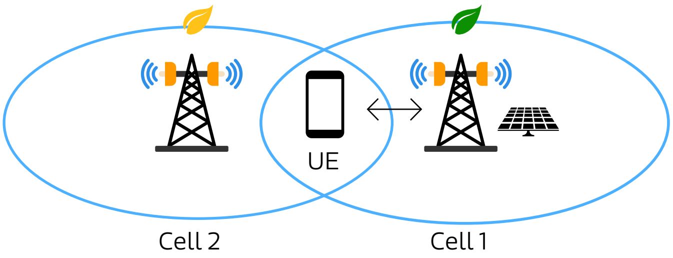

Figure 3-1: Illustration of carbon-aware cell selection

The idea of carbon-aware load balancing is especially pertinent for computing tasks that have the potential to generate significant carbon emissions, owing to their heavy computational requirements. The existing systems are mainly designed to support data transfer in a way that, for example, allows finishing compute tasks as soon as possible (high throughput) and/or giving results as soon as possible (low latency). However, some compute tasks have flexibility in when and where they are executed; that is, this type of workload could be executed in any computing node and tolerate delays providing the workload gets completed within a relatively relaxed deadline, e.g., at a human rather than computational timescale (AI model training might be such a workload). As shown in Figure 3-2, a user offloads a compute task to the system at a time without available solar power (e.g., New York at 7PM), meaning that executing this task locally will result in some carbon emissions to the air. At the same time, a computing resource located in Los Angeles (at 4PM) is powered by abundant solar energy, i.e., executing the compute task in Los Angeles will be carbon-free. Thus, under the assumption that the energy used to transfer the task from New York to Los Angeles is negligible compared to the energy required for processing the task, the system can adopt this option to reduce the carbon footprint if the delay time for roundtrip communication between New York and Los Angeles can be tolerated by the task. The effectiveness of a carbon-aware workload shift has been demonstrated in [20].

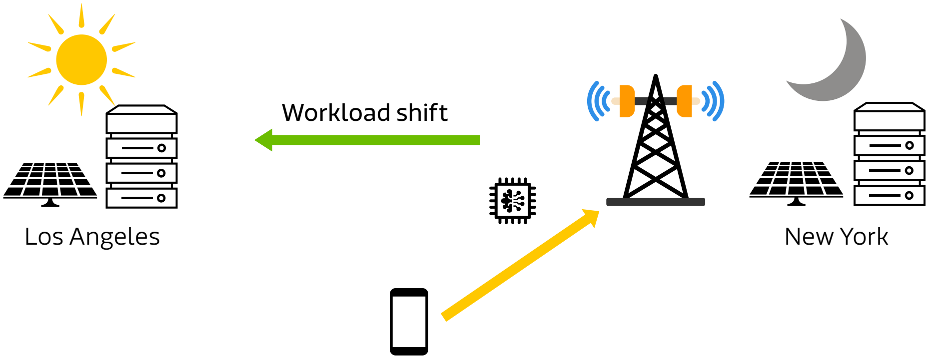

Figure 3-2: Illustration of carbon-aware computation workload shift

3.4. User-Driven Carbon-Aware Service Provision

End users, recognizing that the indirect carbon emissions from services provided by their telecom operators are categorized as Scope 3 activities, can also contribute to reducing these emissions as part of the collective effort to achieve carbon neutrality. Driven by the push from their value chain to cut Scope 3 emissions, these users may engage with their operators e.g. through subscription criteria, to actively decrease Scope 3 emissions. For instance, end users may accept or even demand a controlled level of Quality of Service (QoS) degradation to minimize energy consumption and carbon footprint.

Network slicing can also be exploited to incorporate "end-to-end" carbon-awareness criteria. For example, alternative network slices could offer end-to-end services that have different carbon footprints, influenced by the choice of energy sources, yet still provide similar service outcomes. Subscribers may accept a policy that assigns them to less carbon-intensive slices with minor performance trade-off for lower environmental impact, or more carbon-intensive slices for higher performance demands. Integrating carbon-awareness capabilities into network slicing enables operators to offer a spectrum of sustainable options, empowering subscribers to choose services that match their environmental and performance preferences.

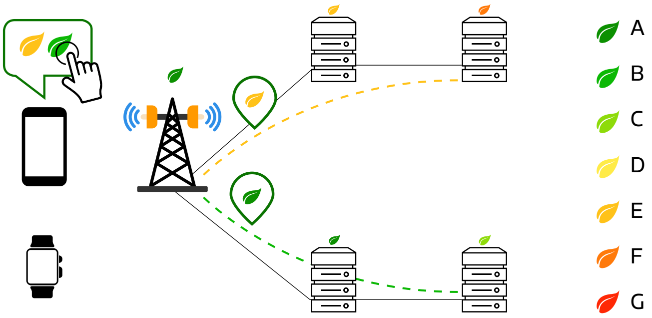

Figure 3-3: Illustration of carbon-awareness for Sustainable Service Provision

As illustrated in Figure 3-3, the envisioned carbon-aware system could offer a "sustainable service" that adjusts QoS in response to renewable energy availability and user preferences. For instance, users will be empowered to specify their preferred level of renewable energy usage, directly impacting the service's allocation of energy from renewable and non-renewable sources, ultimately leading to a reduced carbon footprint of their own service usage and collectively to a reduced carbon footprint of the system as a whole. To enable user-driven carbon-aware service delivery, the introduction of new subscription parameters, policies, and orchestration is essential. The holistic approach empowers users to actively shape the behavior and resource allocation of services, taking into account carbon emissions and renewable energy usage.

- Subscription Parameters: By incorporating carbon-related information and renewable energy usage into the subscription parameters, users can define their preferences during service. This empowers them to influence service behavior in alignment with their requirements, such as renewable energy resource usage, energy efficiency, and carbon intensity criterion.
- Policies: By aligning with sustainability objectives based on user preferences, policies can specify criteria and actions related to carbon emissions and renewable energy usage. This can include enforcing energy-efficient resource usage, prioritizing renewable energy sources, or imposing resource allocation limits based on carbon intensity criteria.
- Orchestration and Management: In the context of carbon-aware service delivery, new orchestration mechanisms dynamically allocate and manage resources based on sustainability criteria set through subscription parameters and policies. This includes monitoring carbon emissions, analyzing resource availability, and making real-time decisions to optimize service delivery for the lowest possible carbon footprint. Orchestration leverages policy-based management frameworks to ensure that service delivery aligns with both user preferences and sustainability goals.

The carbon-aware system should enable user-driven service delivery that considers carbon emissions and renewable energy usage. This approach empowers users to actively contribute to sustainability efforts and supports the transition towards a more environmentally friendly and energy-efficient network infrastructure. In summary, the proposed carbon-aware network operation technology reduces the Scope 2 emissions of operators and the Scope 3 emissions of network vendors.

4. Conclusions

As global mobile network data traffic is expected to grow significantly over the next decade, as new services e.g., computing, sensing will also be introduced, it is crucial to address the constraints on total energy consumption and resulting carbon footprint of the systems used to deliver these services. 6G expected to enter commercial use ca.2030, is under development at MediaTek and other organizations. Our 6G Vision incorporates sustainability, with energy efficiency and carbon-awareness at its core, as a fundamental cornerstone. This whitepaper has reviewed a number of regulatory and other measures introduced or under consideration towards a carbon neutral future and how these will also lead to a transformation of the entire telecom industry. Cooperation between all stakeholders will be essential to introduce support of efficient measures for a sustainable 6G.

In this white paper, we have proposed three primary directions for improving the carbon footprint of mobile networks and battery life of mobile devices:

- Minimize total energy consumption of mobile networks and devices for idle operation
    - Network: Low-power common and paging signals
    - Device: Near-zero-power lite radio
- Optimize energy efficiency of mobile networks and devices for data transmission/reception
    - Network: Energy-efficient waveform, power-scalable beamformer
    - Device: Power-scalable main radio, collaboration with lite radio
- Introduce carbon-awareness in space and time domains for sustainable service provision
    - End-to-end tracking and reduction of carbon emissions via introduction of carbon-intensity metric
    - Carbon-aware resource management based on carbon-intensity criterion, across the system
    - Sustainability- and QoS-driven service architecture for user-centric carbon-aware service

By optimization of energy efficiency, we can mitigate the total energy consumption growth of 6G mobile networks and extend the battery life of 6G devices. Though this progress is essential, achieving a net-zero emission goal requires more than reducing total energy consumption growth. Carbon-aware communication and intelligent green energy utilization for mobile communication and computing in 6G will be pivotal in creating a sustainable communication system. This white paper highlights the importance of sufficient power grid information being available to telecom operators such that they can optimize for reduced carbon emissions. A joint effort to establish further awareness of the needs of the telecom industry in this area would help to drive improvements in this area.

In addition to technologies focusing on energy efficiency and carbon awareness for sustainable 6G, numerous other emerging technologies have the potential to contribute to carbon neutrality, such as innovations in smart grid technologies and energy storage. With a commitment towards achieving net-zero carbon emissions by 2050, MediaTek will continue to drive the evolution of existing mobile communications systems and the development of upcoming 6G, and associated technologies for a sustainable future.

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