WHITE PAPER

Updated Aug. 2024

Sustainable Mobile Networks-Antenna Strategies for Energy Efficiency and Improved Coverage

PROSE

Contents

Section 1 Introduction

From the devastating floods in Australia to the scorching heatwaves sweeping across Europe in the past year, the need for urgent climate action has become unmistakably clear. The mobile industry is stepping up efforts to achieve net-zero emissions, recognizing the imperative to mitigate climate change's impact on our society. By 2023, 62 operators, representing 61% of the industry's revenue and 46% of its connections, have committed to significant reductions in both direct and indirect emissions by 2030, aligning with science-based targets. Additionally, a sizable portion of operators has set their sights on achieving net-zero emissions by 2050 or even sooner. These pledges collectively cover 39% of mobile connections and 43% of global revenue as of 2023.

Beyond the environmental imperative, there's a strong financial motivation for telcos to curb emissions. According to the GSMA report "Mobile Net Zero" in 2023, the telecommunications industry's total energy consumption reached 227TWh, equivalent to the country of Spain's total electricity consumption. This figure continues to rise by approximately 10% annually. From a financial standpoint, telcos expend 141MWh of energy to generate one million euros in revenue, constituting 20-40% of total operational expenditure (Opex) according to the GSMA report 2023.

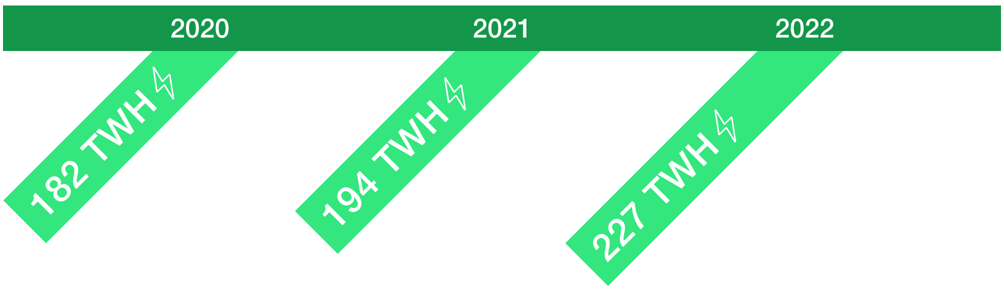


Figure 1: Total electricity usage in telecoms from 2020-2022 (GSMA report 2023)

Meanwhile, Opex outweighs Capex for many telcos, particularly as 4G and 5G networks have been extensively deployed worldwide. Hence, optimizing energy usage efficiency and coverage becomes paramount to reducing energy consumption without compromising user experience. As per the GSMA report (2023), a staggering 80% of the energy bill is attributed to the Radio Access Network (RAN). On average, a single network site consumes 28,665kWh annually, translating to around $5,160 per year per site (based on an average US electricity cost of $0.18/kWh). The subsequent section will delve into the power consumed at the RAN and underscore the importance of focusing on RF efficiency, particularly antenna power efficiency.

Section 2 Power Consumption on 4G RAN Site

Figure 2 presents a simplified wiring layout for a 4G RAN site, showcasing several key components from ground level to the top of the tower. These components include the baseband unit (BBU), external power supply system, remote radio unit (RRU), base station antennas (BSA), associated electrical, optical fibre, and RF jumper cables interconnecting each element. These components can be classified as either active or passive devices based on their need for external power during operation. For instance, RRUs, BBUs, and the power system require external AC/DC power, which are defined as the active devices. Conversely, passive units like base station antennas and cables are designed solely to transmit energy or RF signals to the next stage.

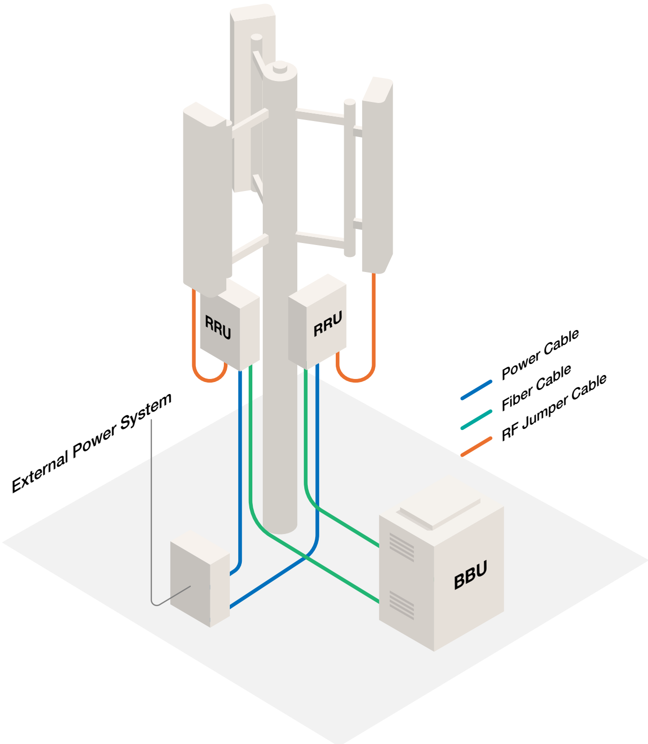


Figure 2: Wiring layout of 4G RAN site

Section 2.1 Active Device Efficiency-Power Amplifier

Based on the study of Prof. Peter Grant (Manz, B., date not available) shown in Figure 3, 40% of power including power amplifier, transceiver power conversion and combining/duplexing is directly RF related. The other 33% consumed for power supply, cooling, transmit power, electrical cabling losses are indirectly related to RF. Therefore, it is safe to draw conclusion that about half of the AC power is consumed for RF purposes on site.

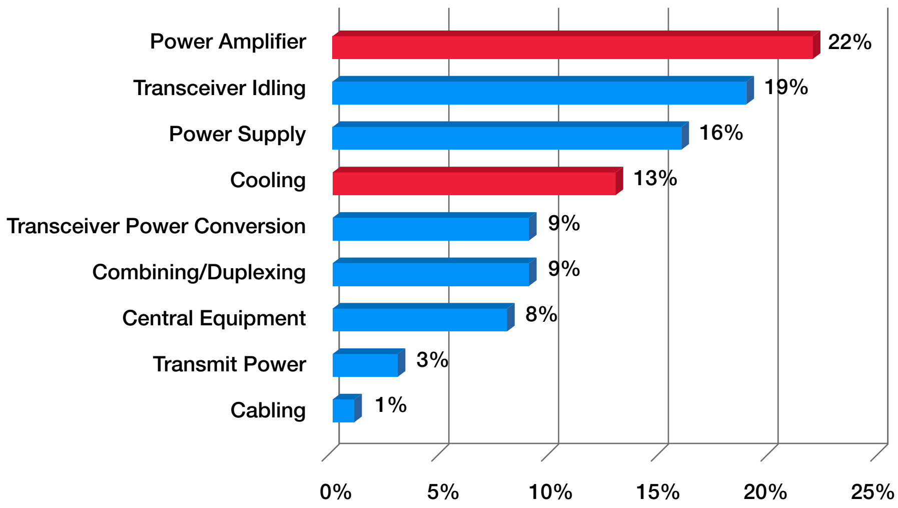


Figure 3: Power consumption among different active components (Manz, B., date not available).

The power amplifier within the RRU stands out as the primary consumer of electrical energy, impacting other active elements such as cooling and power supply systems.

A simplified schematic of the power amplifier is depicted in Figure 4. The efficiency of the power amplifier is quantified using the parameter known as power added efficiency (PAE), calculated by Equation (1). PAE represents the ratio of output amplified RF power minus the input RF power to the consumed DC power for amplification, expressed as a percentage.

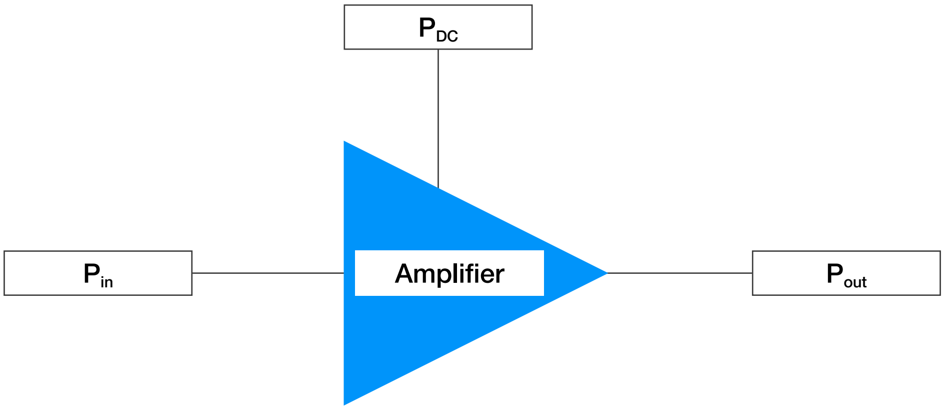


Figure 4: Power amplifier schematic

$$PAE = 100 \times \frac{P_{OUT}^{RF} - P_{IN}^{RF}}{P_{DC}^{TOTAL}} \quad (Eq\ 1)$$

LDMOS (Laterally Diffused Metal Oxide Semiconductor) has become prevalent in base station radios for LTE networks, gradually replacing bipolar transistors due to its relatively higher efficiency and linearity (Theeuwen, H. 2012). However, achieving 50% PAE remains a challenge with LDMOS technology. Another emerging technology, GaN (Gallium Nitride) amplifier, shows promise with a potential PAE of 60% or higher, though at the expense of linearity. Yet, as LTE and 5G modulation schemes grow in complexity, maintaining sufficient linearity for demodulating uplink signals from mobile phones becomes increasingly crucial. Consequently, the industry faces hurdles in enhancing active component efficiency while maintaining affordability and performance.

Section 2.2 Passive Device Efficiency

Passive device efficiency therefore becomes more important to improve the total system efficiency. RF jumper cable and base station antennas are the major two contributor to the passive losses.

Typical jumper cable is 1/2 inch in diameter and 1-3 meter long between the RRU and base station antenna. The length depends on the site installation and antenna length. This type of cable is loaded with formed PE (polystyrene) material between the inner and outer conductor for minimal loss as shown in Figure 5. It is about 7-12dB/100m below 1GHz and 12.5-20dB/100m at 2.7GHz. It converts to 92% at low band and 87% at high band efficiency in the worst case assuming a 3m jumper cable used. It is crucial to rout the jumper cable as short as possible.

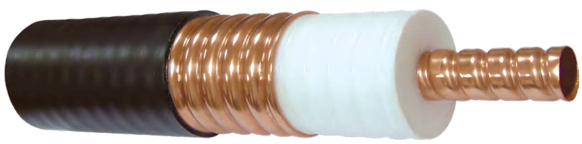


Figure 5: Internal structure of RF jumper cable

RF power will enter the base station antenna before eventually radiate into the air. A typical RF path within a base station antenna includes components like input cables, phase shifters, phase cables, splitter feed boards, and radiators as shown in Figure 6. Loss occurs at each stage, categorized into direct material loss and return loss (indirect material loss) due to impedance mismatch. The losses eventually convert into heat. Conventional BSA antennas typically exhibit a 70% efficiency between the power from the input cable to the power radiated out from radiator, with losses generating heat inside the antenna or reflecting to the RRU, causing further issues.

This power efficiency is given the name as antenna power efficiency related to the material losses PE_{ml}. The equation is given as below.

$$PE_{ml} = \frac{RF\ power\ radiated\ into\ the\ air}{RF\ power\ to\ the\ input\ cable} \quad (Eq\ 2)$$

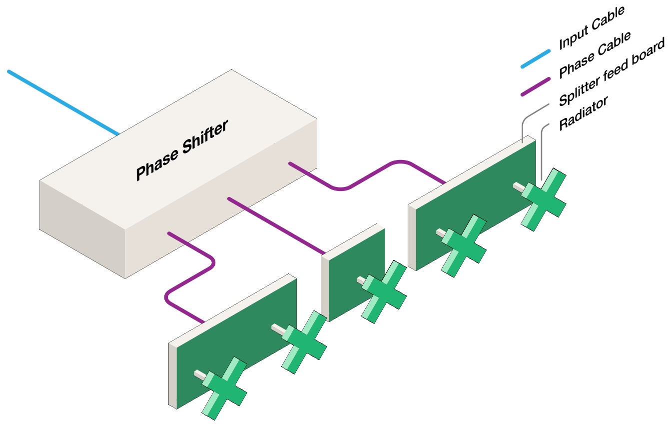


Figure 6: Wiring diagram of conventional base BSA feeding network

As discussed previously, the active device in the system is challenging to be improved. Moreover, the passive device such as jumper cable is already very good by itself. Therefore, it is more needed to further improve the antenna power efficiency. The benefits of having a high efficiency base station antenna are summarized as below.

1. Potentially Increase the coverage areas
    a. Increased radiated power enhances gain or coverage area potential.
    b. Reduced heat accumulation within the antenna enhances the long-term reliability or allows for higher power transmission for expanding coverage.
2. Potentially using a shorter/smaller antenna with reduced wind load to get the same coverage.
    a. The tower building cost is reduced because of structural integrity is reduced.
    b. Saving more space on the tower particularly for the length means more antennas could be installed on the same tower for better user experience.
    c. Opex cost is reduced as rent of tower space is normally calculated based on wind load/antenna size.
3. Decrease the power amplifier gain in RRU as less power is needed for the same coverage. This could potentially increase the linearity and amplifier efficiency. Indirectly, energy for cooling and AC to DC power conversion is reduced.
4. Less power is needed for covering the same area, simply because the antenna power efficiency PE_{ml} is increased. This will reduce the emission/energy bill directly.

Section 2.3 Solution of Improving the Power Efficiency Related to Material Loss

This medium level PE_{ml} from conventional antennas shown in Figure 6 is mainly due to the loss from the phase cable, feed board and return loss from each of the stage as the structure is rather complex. The RF power must pass multiple stages before reaching to the radiator which cause more potential return loss issues if each component is not well optimized. The phase cable diameter inside the base station antenna is much smaller than the jumper cable as mentioned earlier limited by the internal space and cost of the base station antenna. Its diameter is smaller than 5mm and 200 times more lossy than the jumper cable since it is loaded with plastic rather than low density/loss foam.

In order to improve the efficiency, the key is to reduce the structural complexity and minimize the use of lossy materials. The least lossy practical “material” is air, if not vacuum.

Figure 7 shows the wiring structure of the PROSE PROTREEM product line. The conventional phase shifter has been replaced with an air-fed, low-loss phase shifter that offers improved impedance matching. The phase cable and splitter feed board have also been eliminated, reducing associated material losses and potential return loss. Our measurements show an improvement of PE_{ml} up to 85% from conventional antenna platform 70% with PROSE PROTREEM platform.

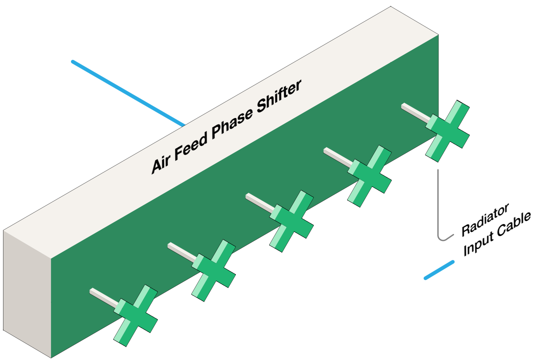


Figure 7: PROSE PROTREEM Product Wiring Diagram

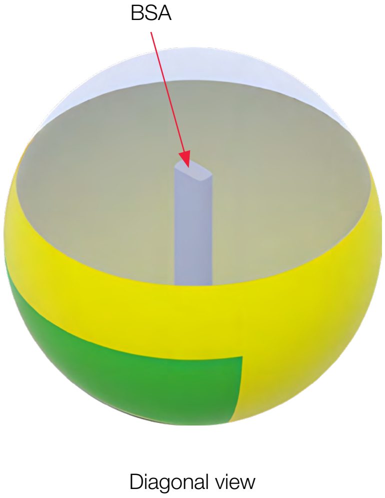
Despite its simplicity, this new structure requires significant redesign of all components for RF, mechanical, and reliability purposes.

In addition, this design allows for individual control of each radiator's phase, as the conventional fixed splitter feed board is replaced. The outcome of fine elevation beam shaping becomes possible, which is crucial for optimizing coverage. This brings us to the following section, which discuss the importance of antenna patterns for improving the coverage and energy efficiency.

Section 2.4 Optimizing Antenna Radiation Patterns for Enhanced Telecommunication Coverage and Energy Efficiency

The solution discussed so far addresses power efficiency related to material loss PE_{ml}. However, it does not consider how effectively this power is distributed into the intended coverage area, which is crucial for energy usage efficiency. The antenna radiation pattern determines this energy distribution. If the antenna pattern is not optimally designed, energy is either wasted in the air or causes interference with other sectors. From this section onwards, we will discuss power efficiency related to the antenna radiation pattern.

A 3D sphere, shown in Figure 8 with a base station antenna in the centre to illustrate the energy distribution for the purpose of telecommunication coverage.



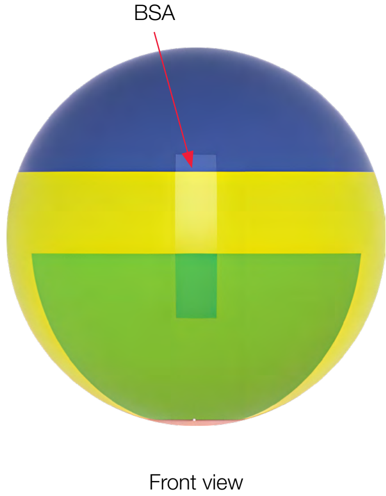


Figure 8: Coloured 3D sphere with BSA in the middle

The sphere is divided into different colours as shown in Figure 9. The detailed illustration of each colour/region is explained below.

Service area/Green area: This area covers the azimuth plane from -60° to 60° and the elevation plane from half-power beamwidth above the tilt setting to 75° below the horizon. This is the area where the energy should be delivered to cover users on the ground.

Interference area/Yellow area: This area is close to adjacent sectors. Energy should be confined within these areas to prevent interference with other sectors.

Useless energy area/Blue area: This area points towards the sky and do not contribute to effective coverage. It does not cause any interference to other sectors. It potentially causes issues for the drones.

Electromagnetic Interference area/Red area: This area is directly under the tower, where humans are most likely to be exposed to emissions. Antenna radiation in this area should be limited to comply with regulations in different countries or regions.

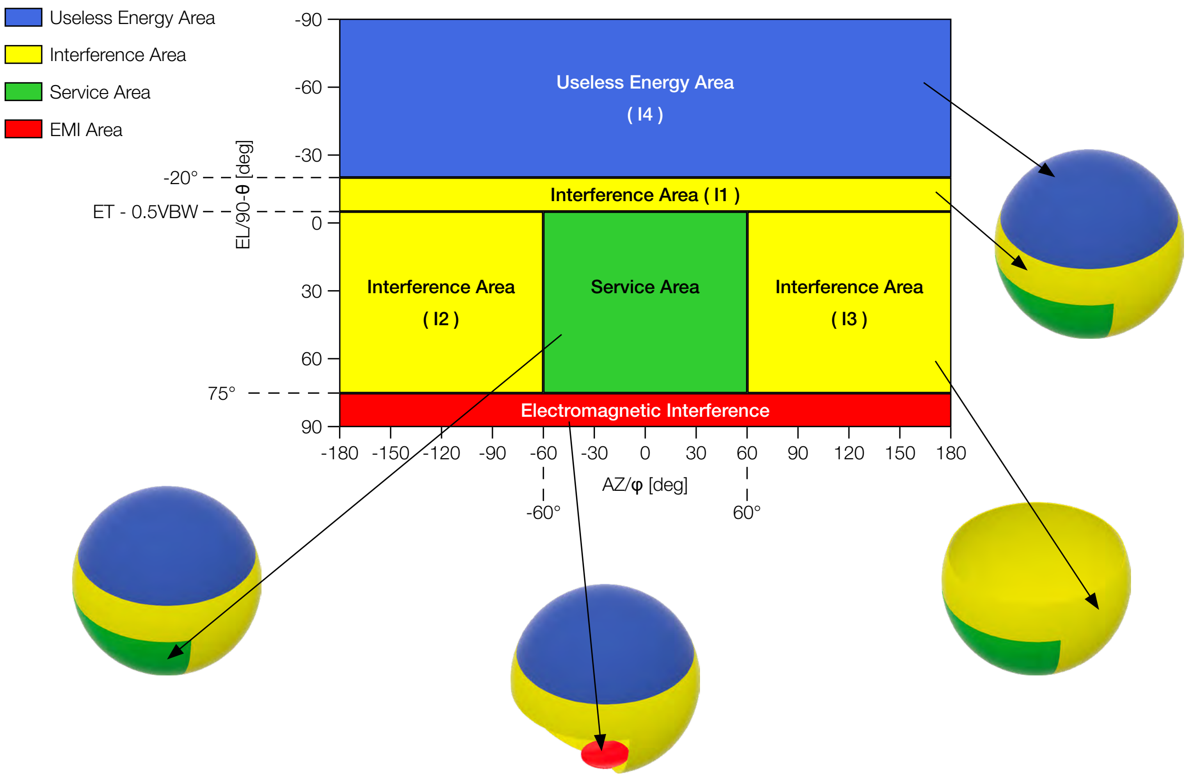


Figure 9: 3D radiation sphere divided into various regions for coverage requirements

One of the major goals of antenna design is to shape the antenna radiation pattern so that it focuses on the Service area in Figure 9. The power efficiency related to coverage requirements can be defined as:

$$PE_{cov} = \frac{Total\ Power\ in\ Service\ Area}{Total\ Power\ in\ All\ Areas} \quad (Eq\ 3)$$

Two important parameters related to energy efficiency are the maximum upper side lobe and azimuth beamwidth, which are discussed in Subsections 2.4.1 and 2.4.2.

Another factor affecting efficiency is polarization purity. Current macro base station antennas are typically linearly slant dual-polarized. The two polarizations are orthogonal to each other, typically ±45°. However, in practice, the intended port always contains a portion of its orthogonal component. For example, an antenna designed for +45° polarization will radiate some energy at -45° polarization. This reduces channel separation, which is critical for MIMO performance, and also represents a waste of energy. The impact of this factor will be discussed in Subsection 2.4.3.

Subsection 2.4.1 Maximum Upper Sidelobe Suppression

The maximum upper sidelobe suppression definition from BASTA is shown below.

“The maximum upper sidelobe suppression is in the elevation cut the gain difference between the main beam peak and the highest level amidst all the sidelobes above the main beam peak and up to the zenith.”

The maximum upper sidelobe is not a problem for coverage or any interference since it is pointed to the sky (Useless energy area in Figure 9). However, it will become an issue if this lobe level is over -10dB or even higher. In this case, it sucks large amount of power and radiates into non-use areas.

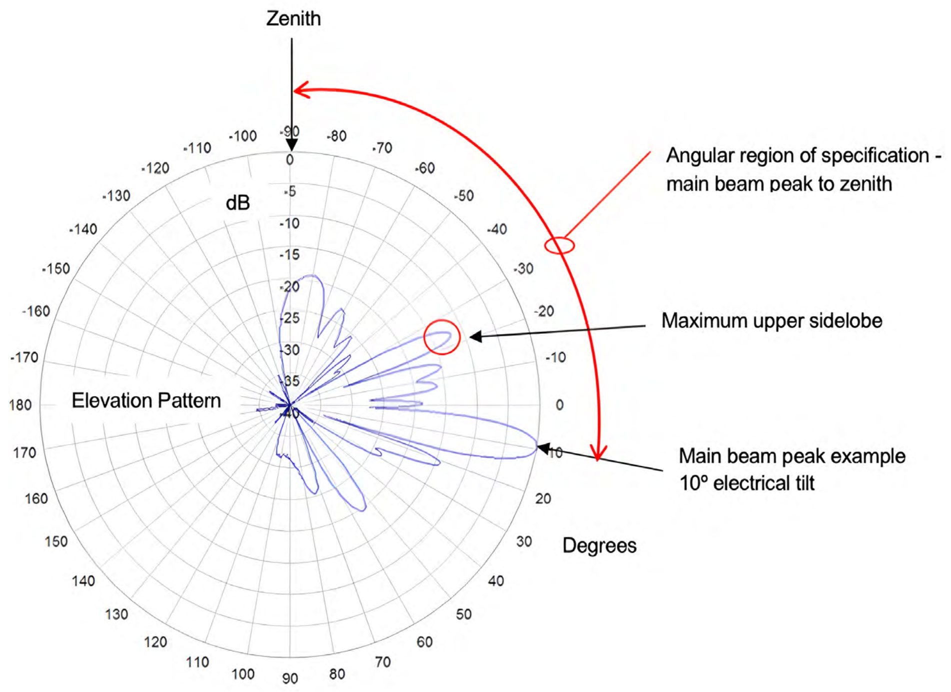


Figure 10: Maximum Upper Sidelobe Suppression Illustration (BASTA V11.1)

This upper side lobe or in other words grating lobe is caused by element spacing larger than half wavelength. It is more deteriorated when the element spacing is over one wavelength. Large element spacing will cause phase alignment at other unintended direction forming grating lobe. The larger spacing relative to the wavelength, the worse the grating lobe will be.

The conventional base station antenna manufactures are using 1:2 ratio of element spacing between LB (below 1GHz) and HB (1.695GHz-2.69GHz). It is because the LB element is in the gap of adjacent HB elements which in return help to decoupling the two bands. However, the element spacing is then locked between HB and LB where the optimal element spacing for each band cannot be implemented. This ends up the large element spacing particularly for HB (1.695GHz/2.69GHz). To overcome this challenge, PROSE Technologies invented a few different decoupling techniques so that LB and HB elements can be placed with large flexibility.

In order to demonstrate the impact of this parameter to PE_{cov}. Simulation of two arrays with two sets of element spacing at the same frequency (2.69GHz) are compared.

The first array contains 6 elements with 120mm spacing and the second array composed 7 elements with 100mm as shown in Figure 11. The number of the element and spacing in the two cases are chosen so that both array's length is identical for fair comparison. The azimuth pattern is the same as well.

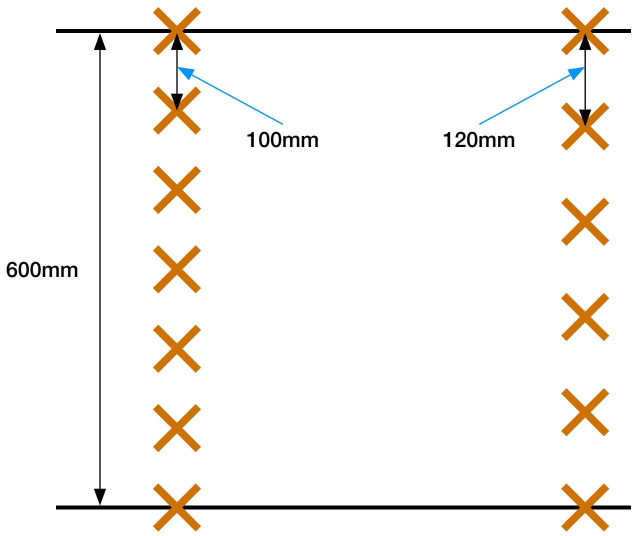


Figure 11: Two array configuration with different element spacing

The elements phase is set to get downtilt at 12°. The element amplitude is set to be equal in this case to maintain simple and fair comparison purposes.

Elevation pattern of two cases is shown in Figure 12. The green curve is the first case with 100mm separation, and the magenta curve is the second case with 120mm separation. The EL peaks of the two cases are both at twelve degrees with the same beamwidth. However, as mentioned before the maximum side lobe is very different.

The 3D patterns of the two cases are also compared in Figure 13. Maximum upper side lobe level is marked.

Based on this simulated 3D pattern, PE_{cov} is calculated shown in Table 1 with relevant gain and maximum upper side lobe.

	Max Upper SL	PE_{cov}	Gain(dB)
CASE 1 100mm spacing	-11.9dB	82.29%	16.9
CASE 2 120mm spacing	-6.4dB	69.81%	16.2

Table 1: PE_{cov} related to element spacing

Clearly, the maximum upper side lobe reduced the efficiency by more than 12% as well as 0.7dB gain. This is significant waste of energy.

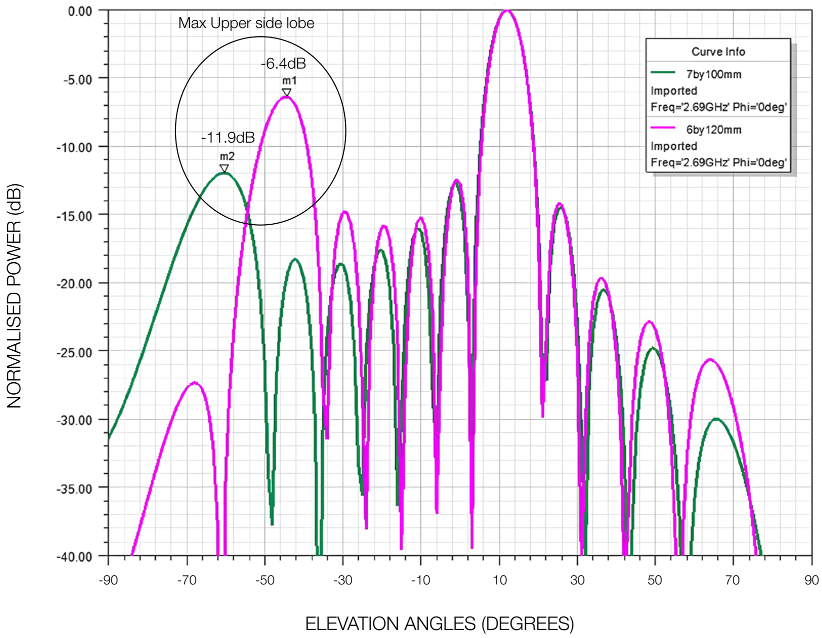


Figure 12: Simulated Elevation Patterns normalised to 0dB of two arrays with different spacing

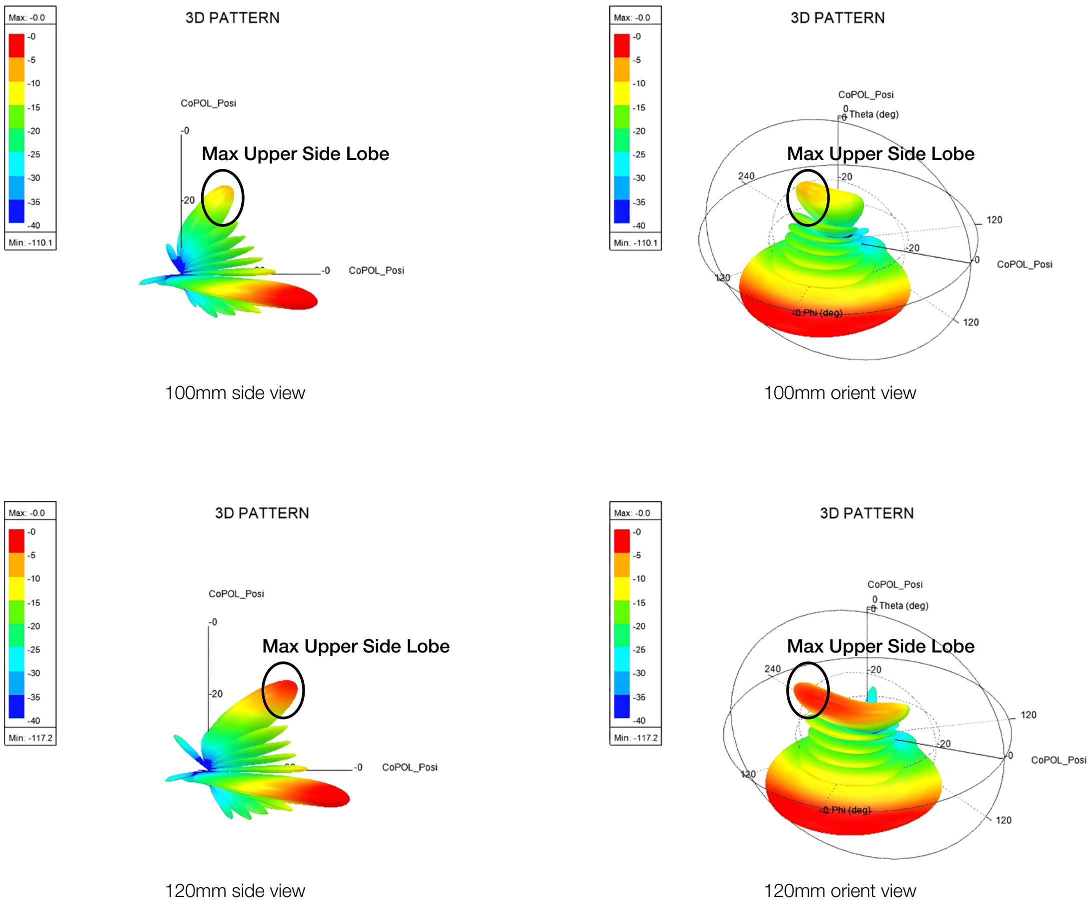


Figure 13: Simulated 3D pattern of two arrays in different spacing

Subsection 2.4.2 Azimuth Beamwidth

3dB (half-power) azimuth beamwidth (AZBW) definition from BASTA standard is quoted below.

"The 3 dB (or half-power) azimuth beamwidth of the antenna is defined in the azimuth radiation pattern as the angular width including the main beam peak, which extends between the only two points at a beam level 3 dB lower than the maximum of radiation, which are also the nearest to the main beam peak."

10dB azimuth beamwidth is the same concept but indicates the beamwidth of the 10dB level. A typical referral 3dB and 10dB beamwidth is 65° and 120° respectively. It is because cellular networks often use a three-sector configuration, where each base station antenna covers approximately 120 degrees of the surrounding area. Using a 65-degree HPBW helps to create some overlap between adjacent sectors. This overlap ensures there are no coverage gaps at the edges of the sectors, providing seamless service to mobile users as they move between sectors. If the beamwidth is narrower, the coverage between different sectors will have a gap. Otherwise, if the beam width is too wide there will be more interference between adjacent sectors. It also means that that amount of power is wasted.

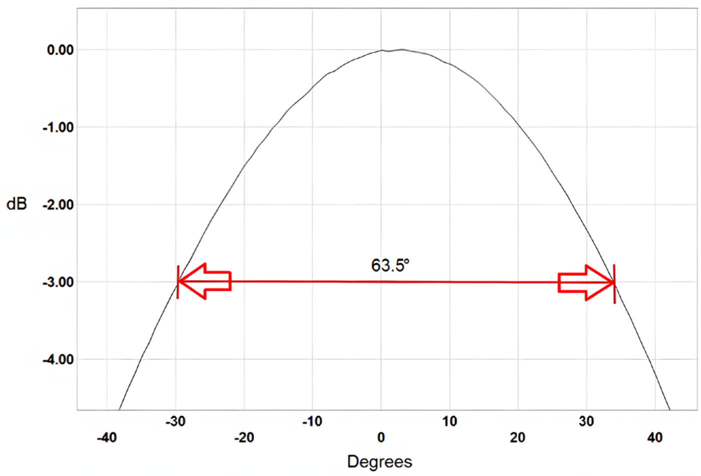


Figure 14: 3dB beamwidth definition

Simulation for studying the important of this factor to the PE_{cov} is conducted. Two cases were simulated again with 120° and 140° 10dB AZBW. AZ pattern is shown in Figure 15. The blue curve is Case 1 with narrower beamwidth. Red curve is the Case 2 with wide beamwidth. The PE_{cov} and associated AZBW is summarized in Table 2. As it is shown, 20° increase of 10dB AZBW reduce the power efficiency by 17%.

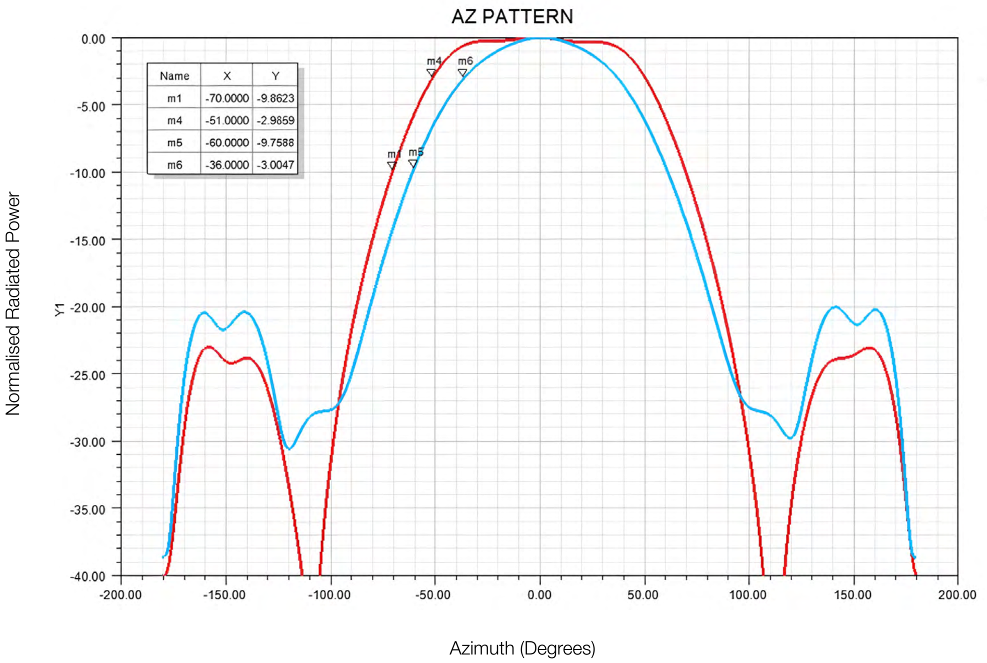


Figure 15: AZBW comparison

	3dB AZBW	10dB AZBW	PE_{cov}
CASE 1	72°	120°	82.29%
CASE 2	102°	140°	65.22%

Table 2: PE_{cov} related to AZBW

Subsection 2.4.3 Cross-Polar Discrimination

Another factor affecting efficiency is polarization purity as mentioned earlier.

Figure 16 shows one of the typical antenna patterns. The black curve is the co-pol pattern which is the intended polarization and red curve is named as cross-pol which is the unwanted polarization.

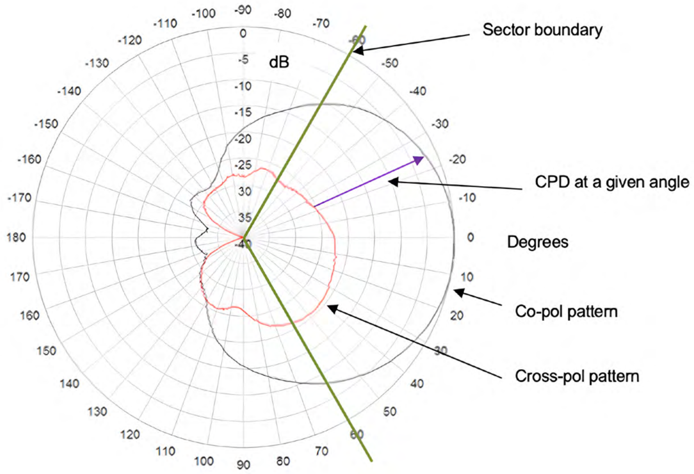


Figure 16: Radiation pattern showing co-pol and cross pol (BASTA V11.1)

The power efficiency related to this polarization purity is then defined in Equation (4).
The total power is the power for intended polarization plus the power for the other orthogonal polarization.

$$PE_{pol} = \frac{Power\ for\ intended\ Polarization}{Total\ Power} \quad (Eq\ 3)$$

One of our test results shows that if the cross-pol signal level is up by 5dB from -22dB. The PE_{pol} dropped by 6% as summarized in Table 3. It shows that is a less important factor in terms of power consumption consideration.

	Average Cross pol level	PE_{pol}
CASE 1	-22dB	97%
CASE 2	-17dB	91%

Table 3: PE_{pol} related to cross pol level

Section 2.5 Overall Power Efficiency

As it is discussed in the previous subsections, the antenna pattern affects the power efficiency in two categories. First, the antenna needs to radiate into service area in Figure 9. Its energy efficiency PE_{cov} is calculated with Equation (3). Secondly, the antenna needs to radiate at the designed polarization. Its energy efficiency PE_{pol} is calculated with Equation (4). However, since the polarization purity is not a significant factor for energy consumption point of view, we will only consider PE_{cov}.

The total power efficiency PE_{total} considering the power efficiency related to material loss PE_{ml} discussed in Section 2.2 can be then calculated by Equation (5).

$$PE_{total} = PE_{cov} \times PE_{ml} \quad (Eq\ 5)$$

Two antenna examples with different performance and its energy efficiency are summarized in Table 4.

Examples	3dB AZBW	10dB AZBW	Max Upper sidelobe	PE_{cov}	PE_{ml}	PE_{total}
Antenna 1	72°	120°	-11.9dB	82.3%	85%	70%
Antenna 2	102°	140°	-7.6dB	58.6%	70%	41%

Table 4: Power efficiency of two different antennas

As Table 4 shows, the energy efficiency of an antenna with inferior design is about 40%, which is almost 30% lower than that of an optimized antenna. This difference significantly impacts both energy consumption and network performance, highlighting the critical importance of radiation optimization.

Even though multiplication operator is used between the power efficiency of coverage and power efficiency of material loss because those two factors are independent. It is only one indicating parameter for the energy consumption. To optimize the network performance overall, all antenna parameters such as AZ/EL beamwidth, front to back, passive intermodulation needs to be considered. The total energy efficiency PE_{total} only makes sense if other fundamental performance is met rather than a sole performance driven the antenna design.

Section 3 Conclusion

To achieve sustainable mobile networks, enhancing energy efficiency and improving coverage are crucial. The mobile industry is responding to the urgent need for climate action, with many operators committing to significant emissions reductions by 2030 and aiming for net-zero by 2050. This commitment aligns with both environmental imperatives and financial motivations, as the industry's energy consumption is substantial and continues to grow.

A key area for reducing energy consumption is optimizing the Radio Access Network (RAN), which accounts for the majority of a telecom operator's energy use. However, improving the efficiency of key active and passive components, such as power amplifiers and jumper cables, remains challenging due to high costs and performance constraints. Therefore, innovations in base station antenna power efficiency are essential.

Two critical aspects to improving antenna efficiency are minimizing material loss and optimizing the antenna radiation pattern. Tests and simulations indicate that there is a potential 30% margin for improvement in these areas.

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Glossary

AZ: Azimuth
AZBW: Azimuth Beamwidth
BBU: Baseband Unit
BSA: Base Station Antenna
EL: Elevation
F/B: Front to Back Ratio
GaN: Gallium Nitride
RAN: Radio Access Network
RRU: Remote Radio Unit
LDMOS: Laterally Diffused Metal Oxide Semiconductor
Opex: Operational Expenditure
PAE: Power Added Efficiency
PIM: Passive Intermodulation

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