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In contrast to the most common approach to Massive MIMO (multiple input, multiple output) in use today, the innovative dual-polarized beamforming technique developed at Ericsson offers the important advantage of creating broad radiation patterns, while avoiding the underutilization of power resources.

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Massive MIMO is a key 5G technology that is used in most mid-band time-division duplex (TDD) deployments to achieve better coverage, higher user bitrates and increased network capacity [1].

With Massive MIMO, throughput and network capacity can be increased by enabling user-specific beamforming of the data channel, forming narrow beams with high antenna gain pointed at a certain user. Cell-specific transmission is still needed for broadcast and control signaling, however. A common approach to achieve this is to utilize Synchronization Signal Block (SSB) sweeping, wherein multiple narrow beams carrying control information are transmitted in sequence over the intended cell area. The downside of this approach is that it leads to additional overhead, resulting in lower capacity and peak rate. Ericsson offers an alternative approach that enables an efficient realization of cell-specific transmission through the construction of a single broad SSB beam for Massive MIMO.

Ericsson's dual-polarized beamforming (DPBF) technique – also known as array-size invariant beamforming [2,3] – is already widely used in Ericsson radios for various purposes, including creating broad SSB beams. The technique is applicable to both single-SSB and multi-SSB scenarios, and it provides the ability to design radiation patterns to match nearly any cell shapes of interest.

Beamforming basics

To use spectrum as effectively as possible in 5G mid-band TDD deployments, most communication service providers (CSPs) install Massive MIMO radios at the base stations (BSs). A Massive MIMO antenna array provides the BS with beamforming capabilities, which are realized by forming a radiation pattern that amplifies power in certain directions, while muting it in others. This is achieved by applying complex-valued beamforming weights to the radiating elements of the antenna array that define how their individual radiation patterns are combined in the far-field region. As **Figure 1** illustrates, the radiation pattern of an antenna array incorporates two effects: the radiation pattern of a single antenna element, and the so-called array factor due to the superposition of the radiated electric fields of all the array elements. The radiation pattern of an array is a product of both the element pattern and the array factor.

A popular choice of the beamforming weights is based on discrete Fourier transform (DFT) vectors that ensure narrow beams with maximum possible array gain. In this way, the BS can direct the transmitted energy toward a user mobile terminal (user equipment (UE)), which can increase

Terms and abbreviations

3GPP – 3rd Generation Partnership Project | **BS** – Base Station | **CSP** – Communication Service Provider | **dBi** – Decibels Relative to Isotropic | **DFT** – Discrete Fourier Transform | **DPBF** – Dual-Polarized Beamforming | **HPBW** – Half-Power Beamwidth | **LTE** – Long Term Evolution | **MIMO** – Multiple-Input, Multiple-Output | **NR** – New Radio | **PA** – Power Amplifier | **PBCH** – Physical Broadcast Channel | **PDCCH** – Physical Downlink Control Channel | **PDSCH** – Physical Downlink Shared Channel | **RSRP** – Reference Signal Received Power | **SINR** – Signal-to-Interference-plus-Noise Ratio | **SSB** – Synchronization Signal Block | **TDD** – Time-Division Duplex | **UE** – User Equipment

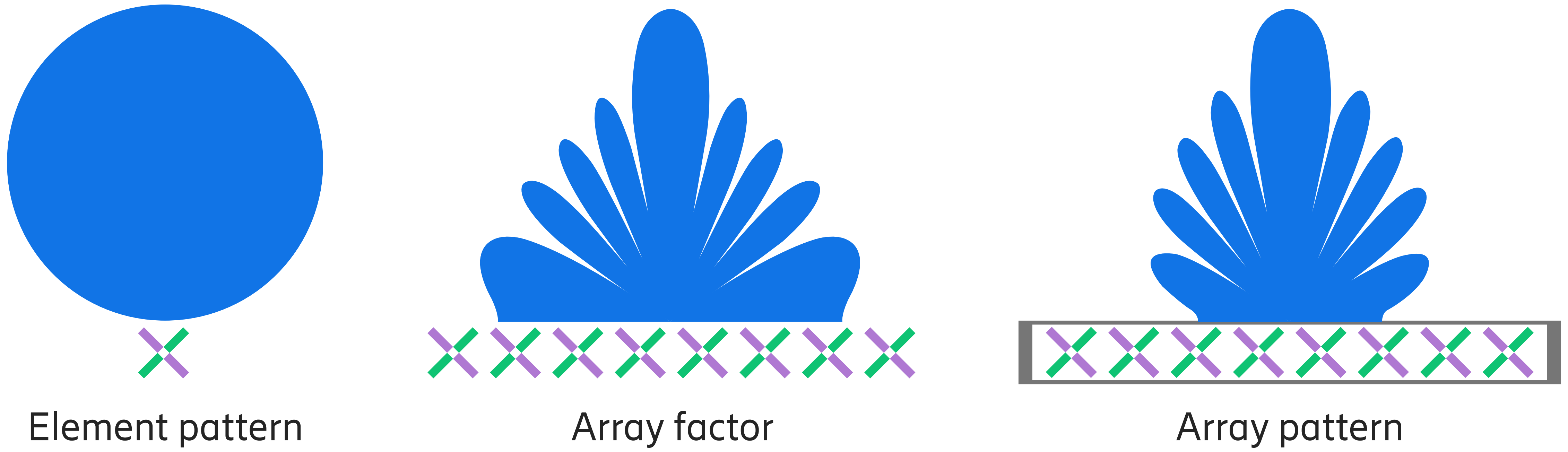

Figure 1: Pattern multiplication property

the received dedicated signal power at the latter and consequently improve its data rate. The larger the antenna array at a BS, the narrower its radiation pattern can become, and the larger the gain of such user-specific beamforming. Corresponding beams are often referred to as traffic beams (or user data beams) and they are essential for transmitting data.

Meanwhile, there are situations where it is beneficial to transmit signals to many UEs at once or when the channel state information to a UE is outdated or unknown. Such transmissions could be related to synchronization, initial access or mobility signaling. This may be particularly relevant for control and broadcast channels, such as the physical downlink control channel (PDCCH) and the physical broadcast channel (PBCH), as well as cell-specific signals for mobility, such as SSB. Such channels are characterized by the broadcast nature of the information and low bitrate per user. For such cell-specific transmission, a broad beam (or a limited number thereof) is needed to cover the entire macro sector with a roughly even radiation level.

Unfortunately, for large antenna arrays, creating a broad beam is not straightforward. Direct enlargement of the array aperture leads to the immediate shrinkage of the radiation pattern. There are, however, ways to overcome this challenge. The simplest approach to create a broad beam is to transmit with a single antenna element, which typically has a broad radiation pattern. Unfortunately, though, this approach results in hugely underutilized power resources, which leads to significantly reduced coverage.

Various beam-shape optimization algorithms have been used in industry and academia to obtain broader beams with certain levels of imperfection. Some of these tune amplitudes of the beamforming weights of certain antenna elements in the array to obtain a broad beam. Others exploit only phases of the beamforming weights to broaden the beam shape. Both approaches have advantages and disadvantages. Most notably, amplitude tapering produces spatially broad beam patterns at a cost of reduced total transmit power, while phase tapering preserves full power utilization at a cost of spatial ripples in the beam shape [4].

An alternative method for covering a sector relies on performing a sweep over a set of narrow beams. Such sweeps constitute a common approach used for beam management procedures in 5G New Radio (NR). For example, instead of transmitting a single SSB utilizing one broad beam, multiple SSBs are sequentially transmitted in what is known as a "synchronization signal burst" containing a set of narrow beams spanning the angular directions of the sector. This solution provides high antenna gains for the entire sector coverage. However, it leads to increased overhead and complexity, which increases with the number of SSB beams to sweep over. The solution also leads to increased UE battery usage because the UE needs to actively listen for an SSB during the entire sweep procedure.

Academic papers have proven that, for a given polarization, transmission from a single element is the only possible solution to produce a broad beam with a spatially flat array factor [5]. These findings led to the belief that the creation of broad beams with full power utilization might not be possible and that SSB sweep was needed to achieve good SSB coverage. Based on this, some experts advocated for 3GPP (3rd Generation Partnership Project) to mandate SSB sweep for beam management in 5G NR but after careful consideration, 3GPP opted for flexible control channel configuration instead. As a result of that decision, our mid-band radios are able to employ a single broad SSB beam without any beam sweep. Thanks to an Ericsson innovation, broad beams can be created without compromising on power amplifier (PA) utilization.

Ericsson's dual-polarized beamforming technique

In 5G NR, the downlink data transmission over the physical downlink shared channel (PDSCH) is decoupled from that of the SSB. Hence, there is no direct correlation between the reference signal received power (RSRP) and the signal-to-interference-plus-noise ratio (SINR) measured on the SSB to the data transmission performance. The latter is addressed by the traffic beams during the data transmission phase. Note that this is different from 4G LTE (Long Term Evolution), where the RSRP/SINR measured on the cell-specific reference signal is tightly coupled with the bitrate performance. Meanwhile, in 5G NR, the SSB is mostly used for providing coarse synchronization, radio link monitoring, open-loop uplink power adjustments, PBCH decoding in initial access and cell selection/detection as part of mobility procedures.

For large antenna arrays, creating a broad beam is not straightforward.

PBCH is a very robust channel and can be decoded at very low SINR conditions; typically, other channels in the initial access procedure have lower link budgets. Thus, PBCH does not constitute a coverage bottleneck and improving SSB RSPR/SINR through beam sweeping may therefore not result in higher effective coverage or robustness. Considering mobility, the relative differences in RSRP/SINR between SSBs of different cells is what matters for proper cell association. An increase in antenna gain of the SSB will therefore not lead to better mobility decisions. In fact, SSB beam sweeping might even be detrimental to mobility performance when using RSRP/SINR-based mobility, as interference conditions are not captured accurately.

Given these observations, a trade-off can be formulated between the increased antenna gain and the increased overhead and latency introduced by a beam sweep. Thus, excessively increasing the number of SSB beams beyond the optimal trade-off point will not lead to increased NR coverage in practice but may only reduce system performance due to the increased overhead [6].

The DPBF technique provides a means of creating broad beams with a spatially flat array factor.

The optimal number of SSB beams depends on the frequency band and the size of the antenna array. For sub-4GHz, for example, a single SSB beam is deemed sufficient, while for millimeter wave frequencies, 12 SSB beams are typically used for macro deployments. The upcoming spectrum between 6-15GHz may need a number in between, depending on the antenna size. Regardless of how many SSB beams are deployed, a power-efficient method is needed to synthesize beams with the desired radiation properties.

To design broad beams with excellent power utilization, Ericsson researchers developed the DPBF technique. The approach is based on the fact that modern antenna systems are naturally built to exploit a pair of orthogonal polarizations. This dual-polarized nature provides an additional degree of freedom to design a radiation pattern purely by means of phase-only techniques, removing the limitations of the amplitude-tapering methods.

The DPBF technique makes it possible to achieve a range of beamwidths with large antenna arrays, while guaranteeing efficient PA utilization. This can be used for the purpose of cell shaping, where the beam shapes and pointing directions are adapted in a coordinated manner across cells for cell-defining signaling, such as SSB in 5G NR. This implicitly determines which cells serve the UE, providing a means for reducing interference and load balancing among the cells.

To realize a broad radiation pattern from a dual-polarized antenna array, it is necessary to excite the radiation elements in two polarizations by a pair of Golay complementary arrays [7]. These pairs were discovered by the Swiss mathematician and physicist Marcel Golay in 1949 within the field of multi-slit spectrometry [8]. Their distinctive property is complementarity, which means that the power spectral densities of the two arrays complement each other and add up to a constant for all frequencies. Because we know that the (power-domain) array factor of a beam is related to the power spectral density [2], applying complementary beamforming weights results in per-polarization radiation patterns that, although they are not broad themselves, add up to a broad-beam pattern with an omnidirectional array factor.

The principle is illustrated in **Figure 2**, where the per-polarization beam patterns compensate for each other's nulls with corresponding peaks. The green area indicates a beam pattern in one polarization, while the purple area shows the pattern in the other polarization. Dual-polarized UE observes the total radiation pattern shown in light blue. The total obtained radiation pattern is broad, covering the entire cell with control signaling. UE equipped with two antennas adjusted for two orthogonal polarizations can pick up power from both polarizations and hence observe this broad pattern. Over-the-air trials in a macro-cell scenario [9] have successfully validated NR SSB beams designed using the DPBF approach.

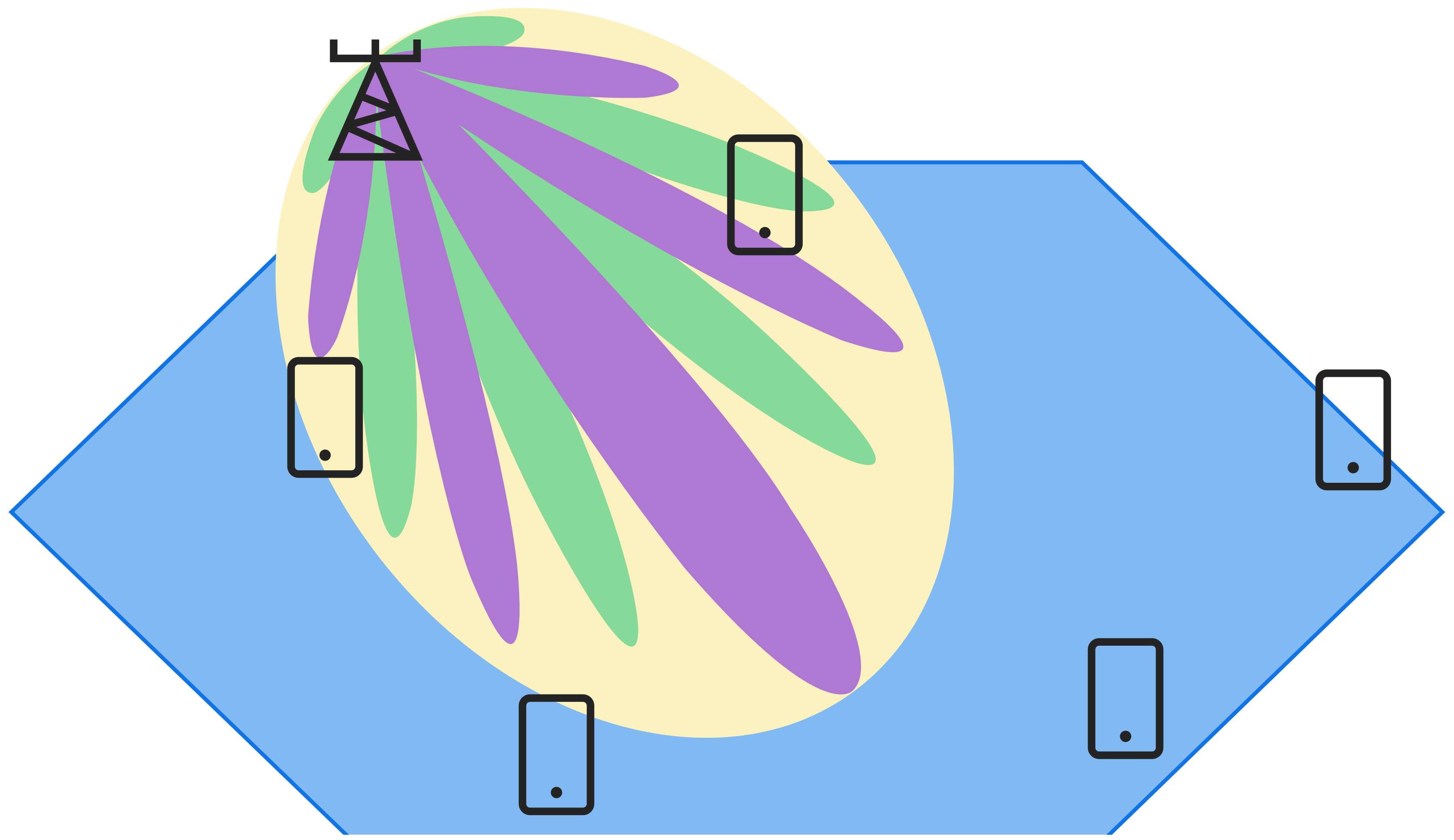

Figure 2: Forming a broad radiation pattern using a dual-polarized antenna array

Dual-polarized beamforming use cases

The DPBF technique provides a means of creating broad beams with a spatially flat array factor. However, most antenna systems are not designed with truly omnidirectional coverage in mind. Instead, they are built to cover an angular sector corresponding to a cell. For example, in a conventional three-sector deployment, a cell has the angular width of only 120°, which means there is a need to design an array factor that is narrower than the omnidirectional one.

Violating the complementarity of the per-polarization beamforming matrices by means of distorting the phases of some of the beamforming weights in a controlled way makes it possible to achieve any beamwidth, ranging from a spatially flat array factor to a narrow DFT beam [10]. This can be used to optimize the radiation pattern to fit the cell shape, use case and deployment scenario of interest. At Ericsson, we design the beamforming weights by combining the complementary phase-only beamforming with a small amplitude taper – with loss of 0.5dB at most, for example – to obtain optimized SSB beam shapes.

The graphs in **Figure 3** are based on a theoretical model representing an active antenna system with eight columns, which is the typical configuration for mid-band products with 32 or 64 branches. Each radiating element has two orthogonal polarizations (slanted +45° and -45°) and a half-power beamwidth (HPBW) of 90°. The figure shows the horizontal farfield patterns of SSB beams designed using the DPBF technique. The target cell shape for the examples in the figure a 120°-wide sector for a typical three-sector deployment. As demonstrated, the DPBF method is useful for creating both broad single-beam designs, such as NR single-SSB, as well as multi-beam designs, such as NR multi-SSB.

The left section of Figure 3 shows an example of a broad-beam design that provides the same cell shape as a Gaussian beam with 65° HPBW. The power radiation pattern (blue) consists of the sum of the +45° and -45° polarized radiation patterns (D+45 and D-45). This beam shape is appropriate for covering a 120°-wide sector with broadcast signaling. However, one potential drawback of this type of Gaussian broad-beam design is that the resulting radiation pattern will most likely not describe the true capabilities of antenna systems with respect to the utilized traffic beams. The data beam capability, which will follow the average embedded subarray patterns, is typically wider than the Gaussian 65°-wide beam.

The middle section of Figure 3 shows an alternative broad-beam design that is also based on the DPBF approach, in which a single SSB beam is optimized to provide improved tracking between SSB and traffic beams. The design target in this case is the envelope of the traffic beams used in the applicable sector. This example shows the results of beam optimization for a sector with a width of 120°, but the method can be used for any sector width. The power radiation pattern (blue) consists of the sum of the two individual polarizations (D+45 and D-45).

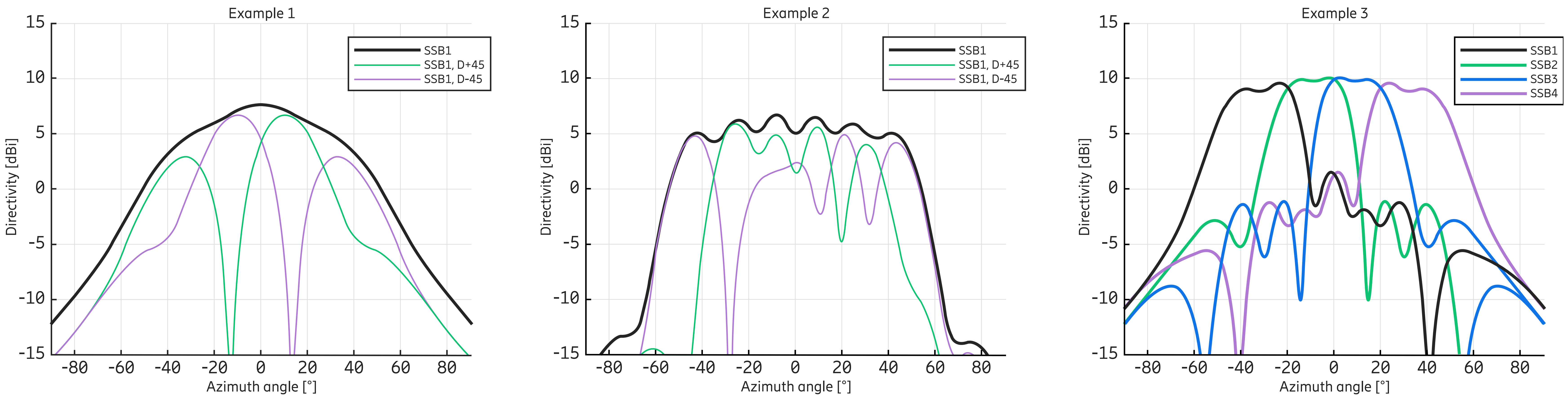

Figure 3 — SSB broad-beam designs using the DPBF technique

The right section of Figure 3 presents a multi-SSB example with four SSB beams, showing the power radiation patterns without individual per-polarization patterns. In this example, the four SSB beams span the desired sector with an increased peak directivity and a reduced ripple in the main beam region.

The three examples in Figure 3 demonstrate the application of the DPBF beam design in the horizontal dimension. The method, however, can be applied simultaneously in the horizontal and vertical dimensions, if desired. Typically, a 2D broad-beam design for antenna systems with many branches can lead to a large and time-consuming optimization. However, oftentimes the desired 2D beamforming weight matrices possess separability properties, and hence the DPBF optimization can be reduced into two simpler optimization problems: one for the horizontal dimension and the other for the vertical dimension.

The DPBF concept also defines how to create a second broad beam with polarization orthogonal to a first broad beam. This can be useful for certain use cases, such as uplink optimization and channel state information reference signal mappings, which may require broad beams in two different polarizations.

Conclusion

Massive MIMO (multiple input, multiple output) is an essential technology to enhance the capacity of 5G networks, most commonly by using narrow traffic beams to improve user data rates. There is, however, also a need for broad-beam coverage that is suitable for broadcast and control signaling, such as 5G New Radio Synchronization Signal Block (SSB). In Ericsson 5G products, SSB beams are created using a dual-polarized beamforming (DPBF) technique that is based on the mathematical concept of Golay array pairs. This innovative technique enables the construction of broad-beam shapes for large antenna arrays without underutilizing power resources. Using this approach, it is possible to design a radiation pattern of an array that defines appropriate cell shapes in relation to user and usage distribution, as well as mobility, which is the essence of a high-capacity cellular system. The DPBF technique can also be used to create broad beams with polarization diversity.

The authors

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