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**INFORMATION PAPER**

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# FREQUENCY SPECTRUM MANAGEMENT PANEL (FSMP)

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**Agenda Item 4a: Radio altimeter technical and policy developments**

## 5G Active Antenna Systems in the unwanted-emissions domain

(Presented by Nicholas Shrout, ASRI)

**SUMMARY**

This paper examines the complexities of modeling 5G Active Antenna System (AAS) antenna patterns in the unwanted-emissions domain. AAS modeling choices directly and significantly affect compatibility assessments for ICAO-protected systems. However, many of the assumptions currently used in studies rely on modeling approaches that may not be fully validated, as AAS behaviors in the unwanted-emissions domain continue to evolve. These uncertainties directly influence regulatory outcomes, highlighting the need for more consistent and bounded modeling practices. This document does not suggest that AAS systems inherently create unacceptable interference, rather it emphasizes that compatibility conclusions depend strongly on the modelling assumptions applied to unwanted-domain directivity.

## 1. INTRODUCTION

1.1 The increasing deployment of AAS in IMT networks has driven the need for accurate modelling of unwanted domain emissions in compatibility studies with aeronautical systems. This document:

- provides a brief overview of the evolution of AAS modelling approaches in the unwanted-emissions domain,
- identifies limitations and non-bounded variables affecting model validity, and
- presents illustrative examples demonstrating that differing modelling assumptions can produce materially different antenna directivity and effective isotropic radiated power (EIRP) in the unwanted domain, thereby altering compatibility outcomes.

## 2. BRIEF BACKGROUND AND EVOLUTION OF AAS MODELING

### 2.1 Pre-AAS (Recommendation ITU-R F.1336)

2.1.1 Prior to the introduction of AAS, models assumed fixed radiation patterns with well-defined sidelobe characteristics. Recommendation (Rec) ITU-R F.1336-5, provides simple parametric parabolic and logarithmic models with few parameters, such as the peak gain and the 3 dB beamwidth.[1] These models are widely accepted within ITU-R studies to bound peak and average unwanted emission antenna patterns. These conventional static antennas provided a stable and predictable basis for interference modelling both in-band and in the unwanted domain.

### 2.2 Early AAS and Beamforming Modelling (Recommendation ITU-R M.2101)

2.2.1 An initial, internationally accepted AAS model was provided in 2017 through Rec ITU-R M.2101. This Rec defines the AAS antenna array model, including how the pattern of a beam-forming array is mathematically expressed, for use in simulation and compatibility work. In this model combining a composite, beam-formed, pattern for the wanted domain with an element-level pattern for the unwanted domain was considered an adequate basis for simulations. ITU-R M.2101-0 states that:

*2.2.2* *"The unwanted signal, caused by transmitter OOB modulation, intermodulation products and spurious emission components will not experience the same correlated situation from the antenna and will have a different emission pattern. A non-correlated AAS has an antenna emission pattern similar to a single antenna element. In an adjacent frequency band situation with IMT as the interfering system, the antenna pattern for the unwanted emission can be assumed to have a similar antenna pattern as a single antenna element."*[2]

*2.2.3* The last portion of this quote implicitly implies that signals immediately adjacent to an IMT emission leave the array fully decorrelated.

### 2.3 AAS with Sub-Array Architectures (Current ITU-R Studies and Guidance)

2.3.1 As AAS technologies matured, hybrid and sub-array architectures became common. The sub-array model now provides a practical basis for in-band modelling.[3] However, assumptions for unwanted-domain shifted toward the single-sub-array model, rather than a single element. This assumption assumes correlation only within the individual sub-array. For the full array of sub-arrays certain interests claim the full array pattern remains fully uncorrelated in the unwanted domain.

2.3.2 Compared to traditional fixed antennas, the number of required inputs increased substantially. Even when focusing only on in-band, parameters include (non-exhaustively):

i. number of radiating elements per sub-array
ii. number of subs-array rows
iii. number of sub-array columns
iv. element gain
v. horizontal and vertical element spacing

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[1] See Recommendation ITU-R F.1336-5 Recommends 2, at pages 2-3, available at: https://www.itu.int/rec/R-REC-F.1336-5-201901-I/en
Note: Although the current version (1336-5) is dated 2019, the first version (1336-0) is dated 1997 and contains similar simplistic models.

[2] See Recommendation ITU-R M.2101-0 Section 5, at pages 25-27, available at: https://www.itu.int/rec/R-REC-M.2101-0-201702-I/en

[3] See Annex 4.4 of the Report on the 50th meeting of WP 5D, Section 3.3, at pages 17-23, available at: https://www.itu.int/md/R23-WP5D-C-0989/en

vi. spacing between sub-arrays
vii. horizontal/vertical 3 dB beamwidth
viii. front-to-back ratio
ix. preset sub-array downtilt
x. array ohmic loss
xi. horizontal and vertical coverage range
xii. mechanical downtilt

2.3.3 This multi-variable vendor specific list compounds the difficulties when attempting to accurately model unwanted-domain antenna patterns.

2.3.4 Further complicating the matter, standardization guidance, institutional mathematical models, and radiated field measurements indicate the unwanted emissions may experience correlation under certain additional architecture-specific and signal-processing conditions such as implementation and effectiveness of Digital Predistortion (DPD) and use and impact of spectral cavity filtering. These elements are discussed in more detail in Section 5 of this IP.

### 2.4 Existing Dilemma

2.4.1 Numerous parameters that remain non-standardized and non-harmonized across industry and regulatory bodies are required to fully characterize AAS unwanted-domain emissions. Further, the gain variance between the single-element, single-sub-array, and fully correlated array cases is substantial.

2.4.2 As a result, regulators should exercise caution when conducting compatibility assessments. There are attempts to characterize a more complete mathematical bound for AAS unwanted-emissions behaviour, but to date, no fully agreed-upon or universally acceptable upper bound modelling approach has emerged.

## 3. EXAMPLE REPRESENTATIVE AAS CHARACTERISTICS

3.1 For illustrative and informative purposes, this section and the following section will use a constrained set of representative AAS variables to emphasize the complexities that may arise in simulations.

**Table-1: AAS With Sub-arrays - Representative Characteristics List[4]**

| Characteristic | Unit | Value |
|---|---|---|
| Rows of Sub-array | # | 4 |
| Columns | # | 8 |
| Elements in Sub-array | # | 3 |
| Single Element Gain | dBi | 6.4 |
| Spacing Between Rows of Sub-array | % of λ | 210 |
| Spacing Between Elements in Sub-array | % of λ | 70 |
| Spacing Between Columns | % of λ | 50 |
| Horizontal and Vertical 3 dB Bandwidth | degrees | 90 and 65 |
| Front-to-back and Sidelobe Ratio | dB | 30 and 30 |
| Sub-array Downtilt | degrees | 3 |
| Mechanical Downtilt | degrees | 6 |

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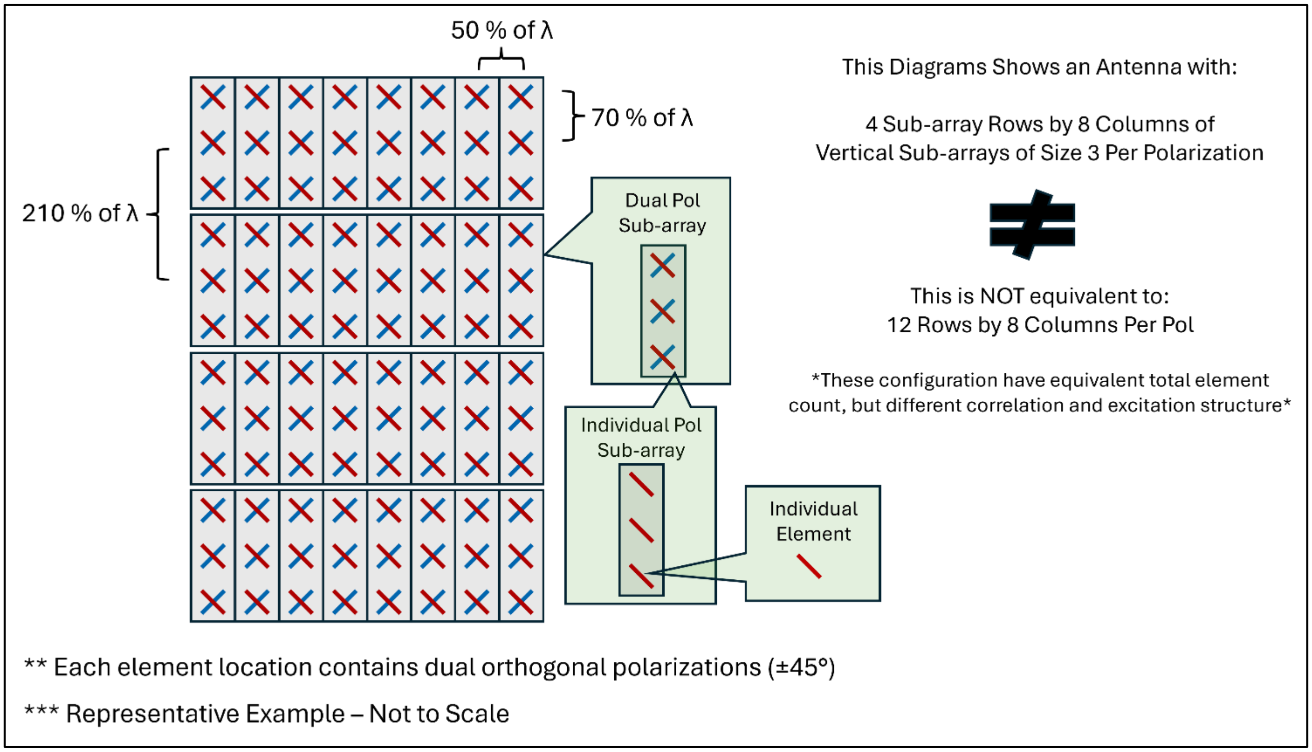
[4] The values in this table are based on proposed beamforming antenna characteristics for proposed IMT in the 4 400-4 800 MHz frequency band found in Annex 4.4 of the Report on the 50th meeting of WP 5D, Table 18, at pages 18-19. See Footnote 3 for reference link.

| | | |
|---|---|---|
| Horizontal Coverage Range | degrees | ±60 |
| Vertical Coverage Range | degrees | 90 - 100 |

3.2 Figure 1 provides an example AAS diagram with a sub-array configuration based on the parameters in Table-1.



This Diagrams Shows an Antenna with:

4 Sub-array Rows by 8 Columns of Vertical Sub-arrays of Size 3 Per Polarization

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This is NOT equivalent to:
12 Rows by 8 Columns Per Pol

*These configuration have equivalent total element count, but different correlation and excitation structure*

** Each element location contains dual orthogonal polarizations (±45°)

*** Representative Example – Not to Scale

**Figure 1: Example of AAS Diagram with Sub-array Configuration**

## 4. ILLUSTRATIVE RESULTS BASED ON REPRESENTATIVE CHARACTERISTICS

4.1 This section provides modelled results for nearly identical configurations with the only variable changing being the correlation of the signal. Figures 2 through 8 use the parameters in table 1 with the AAS beam steered 9 degrees below true horizon. The antenna pattern is rotated to the global coordinate frame to account for BS mechanical downtilt. For comparative purposes the scale in all plots has been fixed to range from -40 dBi to +30 dBi. Figure 9 electronically steers the main beam towards the true horizon and overlays the results for changes in only the correlation factor.

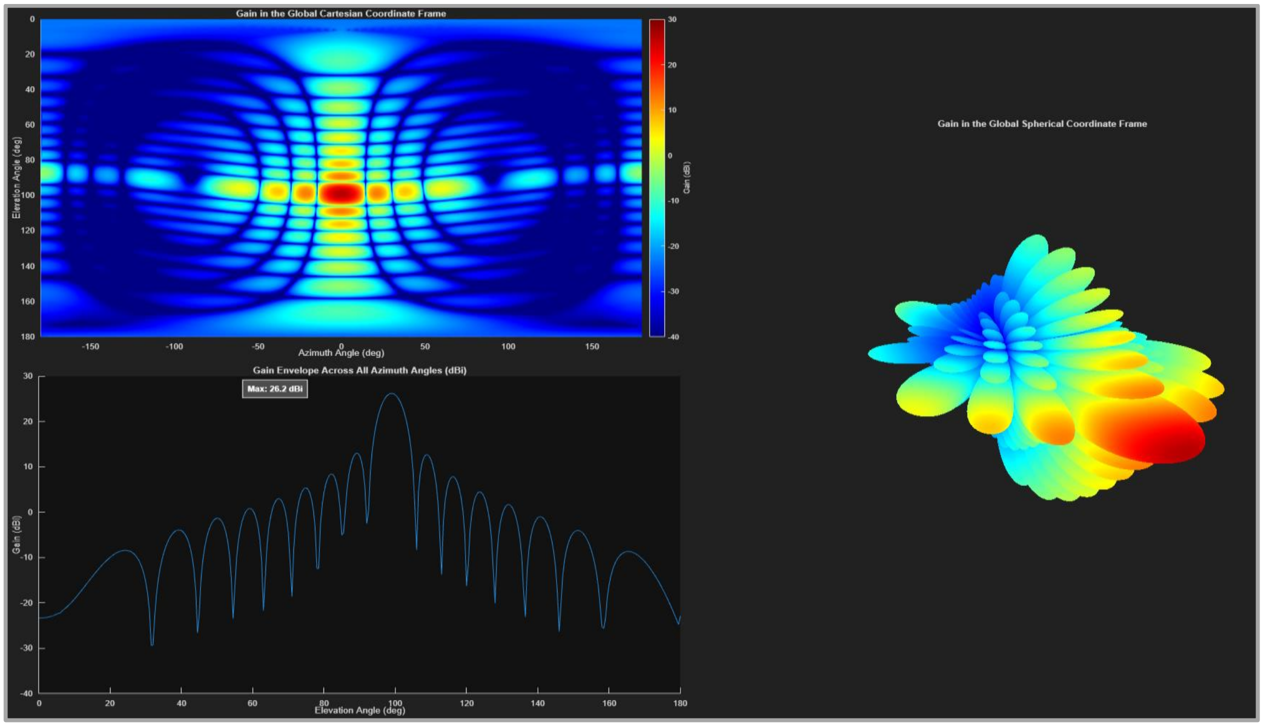

Figure 2: AAS, Sub-array Model - Correlation Factor of 1.0 (Steered 9° Below True Horizon)

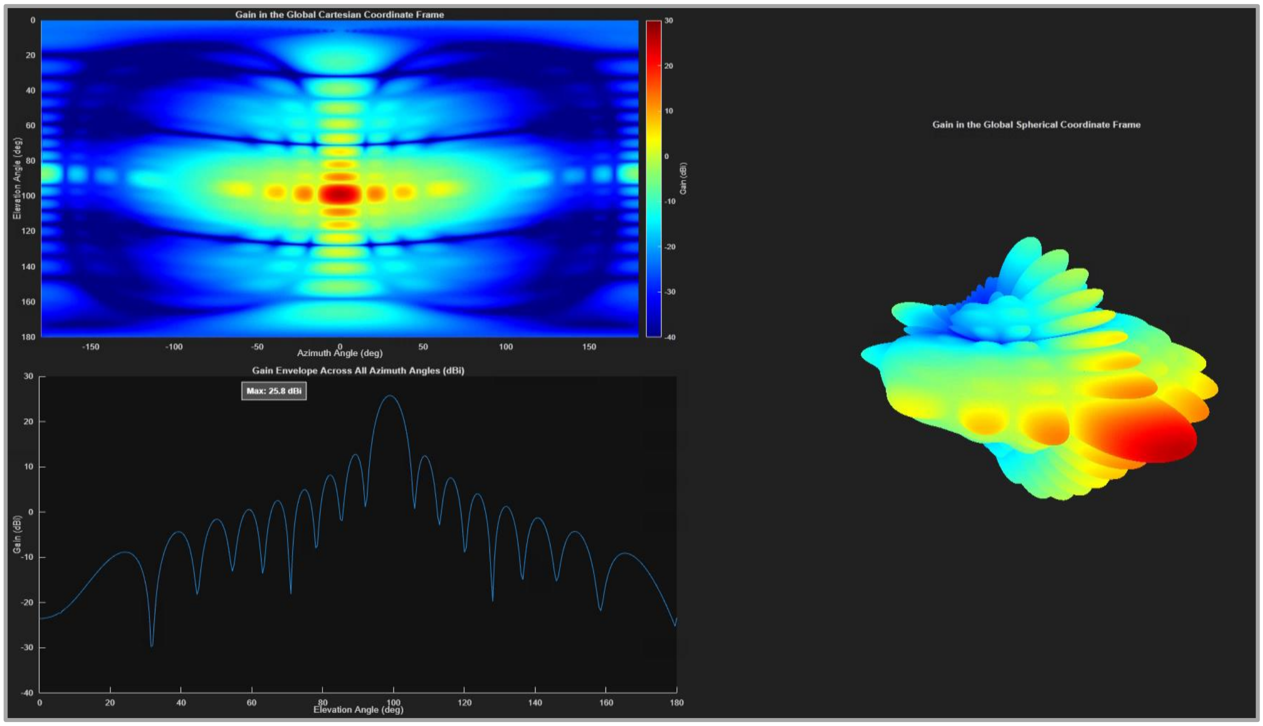

Figure 3: AAS, Sub-array Model - Correlation Factor of 0.9 (Steered 9° Below True Horizon)

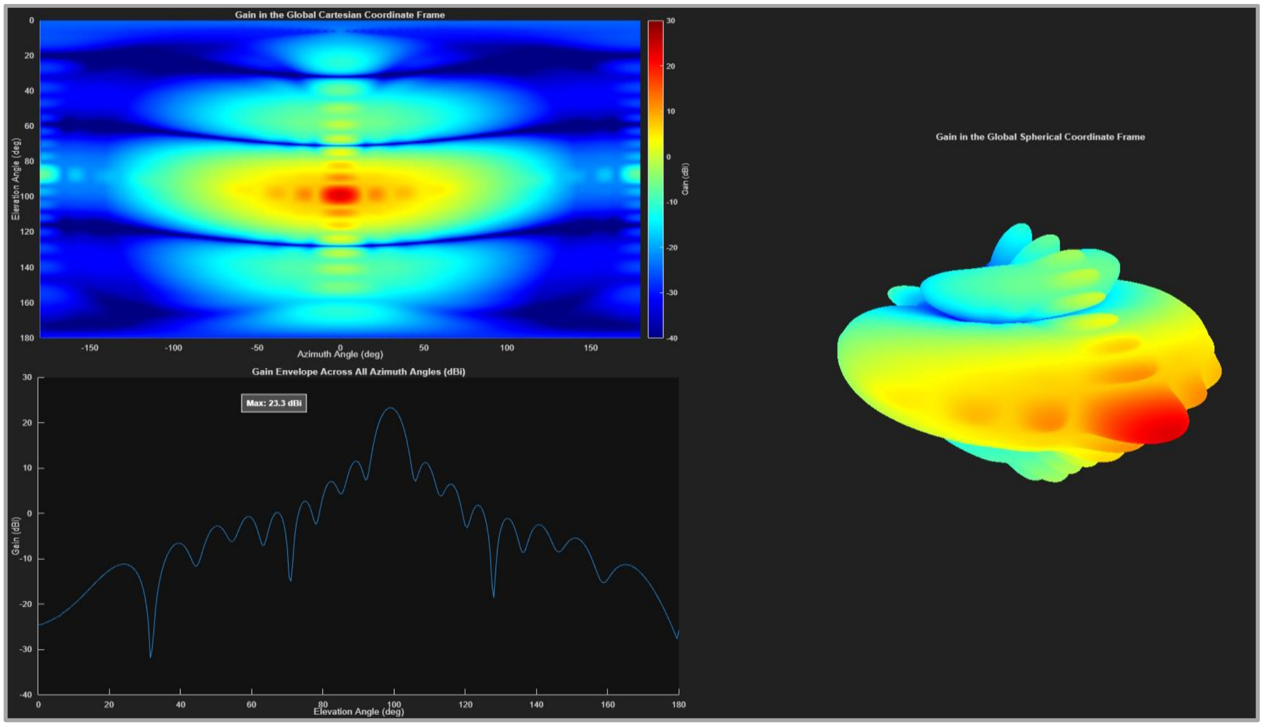

**Figure 4: AAS, Sub-array Model - Correlation Factor of 0.5 (Steered 9° Below True Horizon)**

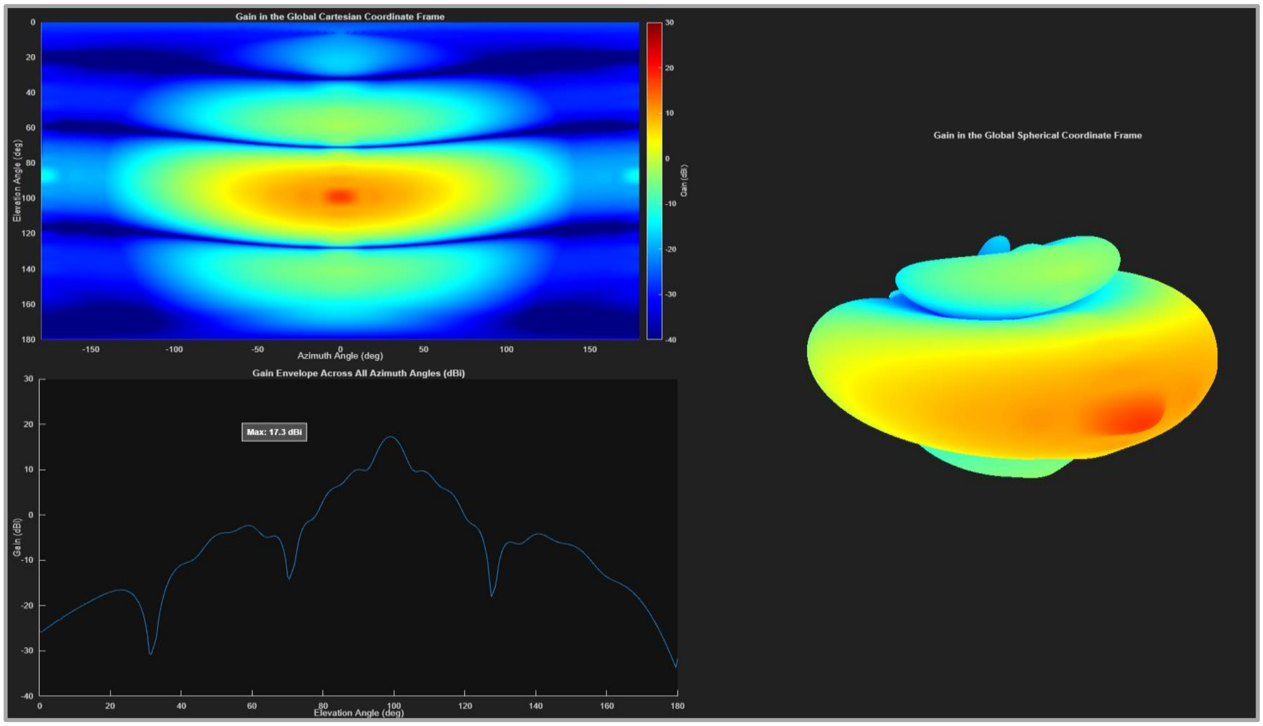

**Figure 5: AAS, Sub-array Model - Correlation Factor of 0.1 (Steered 9° Below True Horizon)**

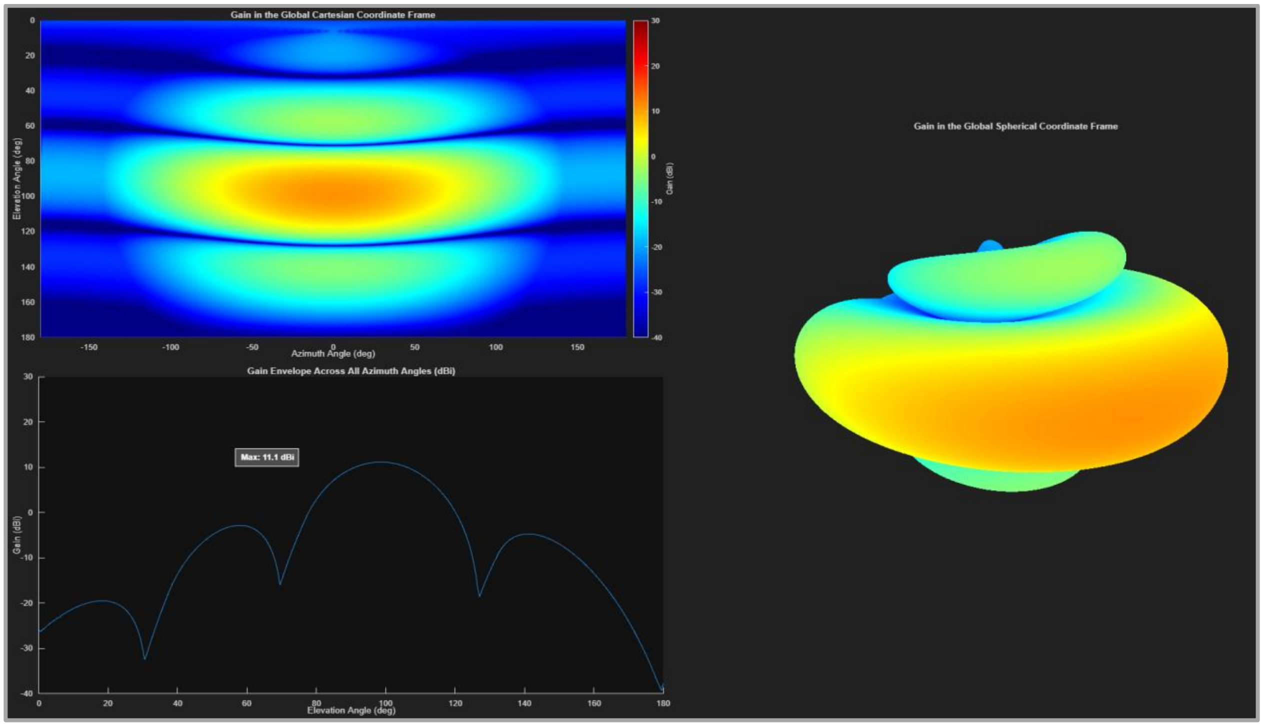

Figure 6: AAS, Sub-array Model - Correlation Factor of 0.0

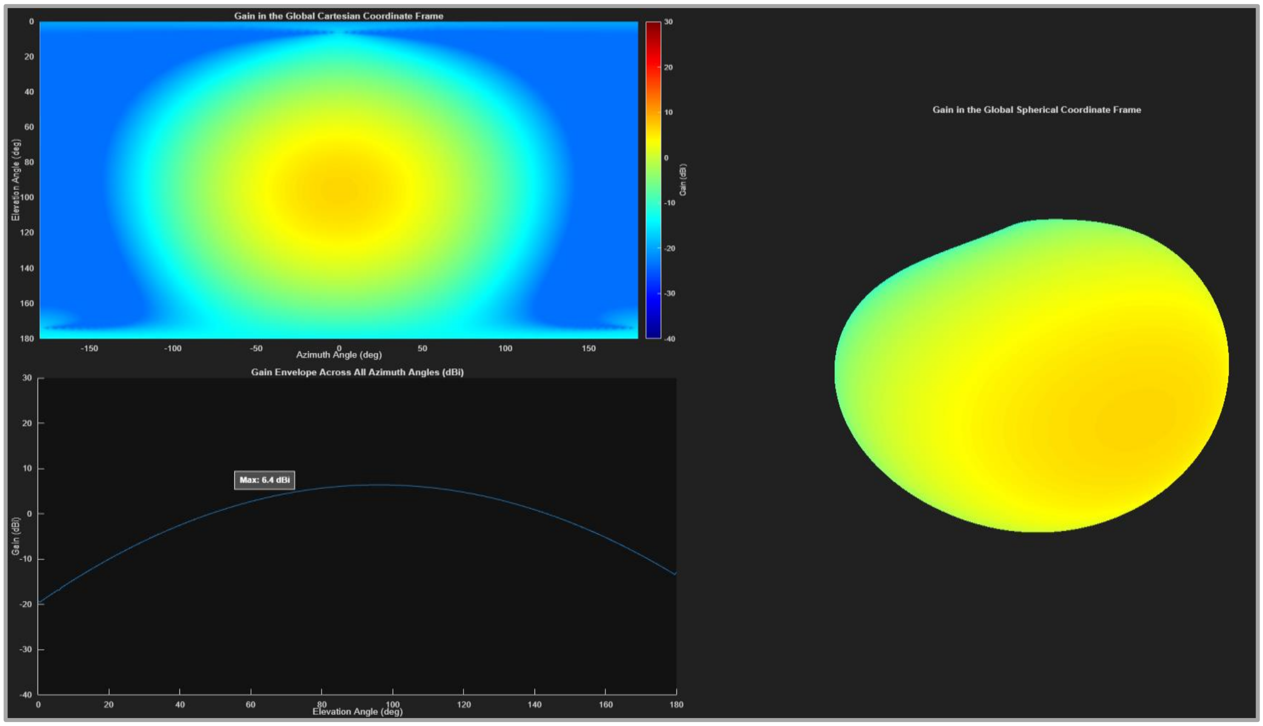

Figure 7: Single Element Gain

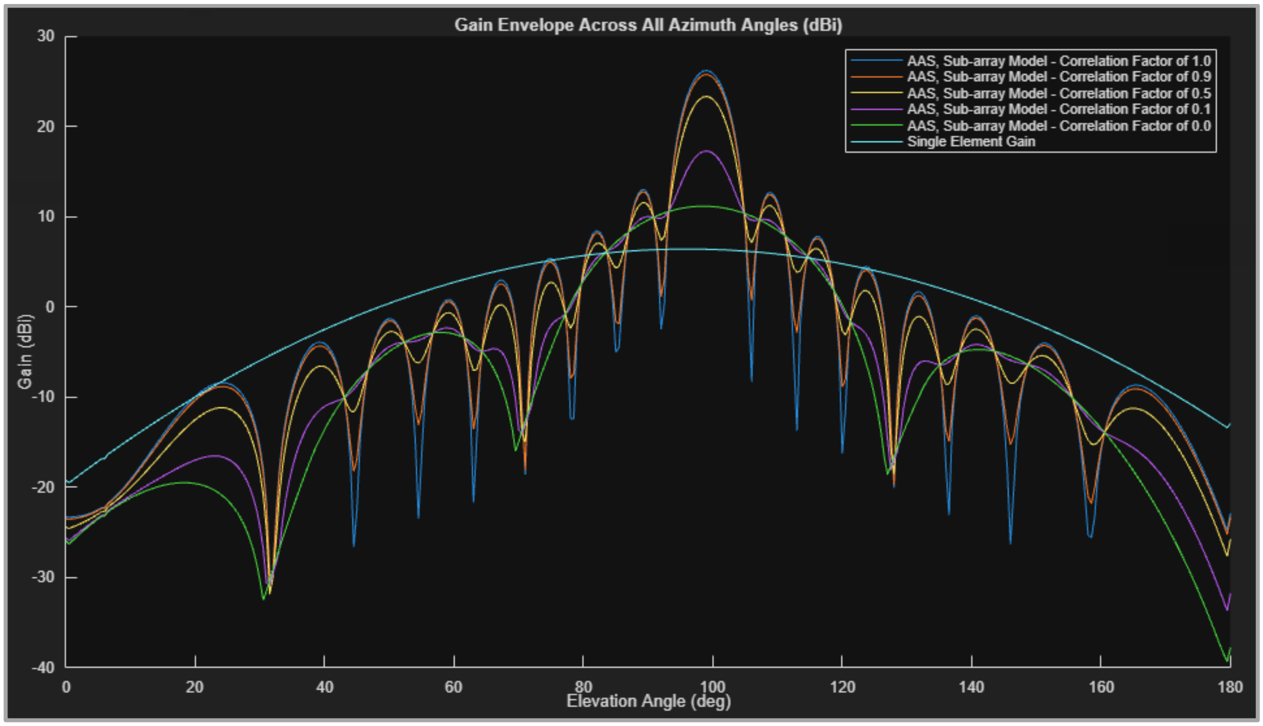

Figure 8: Overlay of Gain Envelope Plots (Steered 9° Below True Horizon)

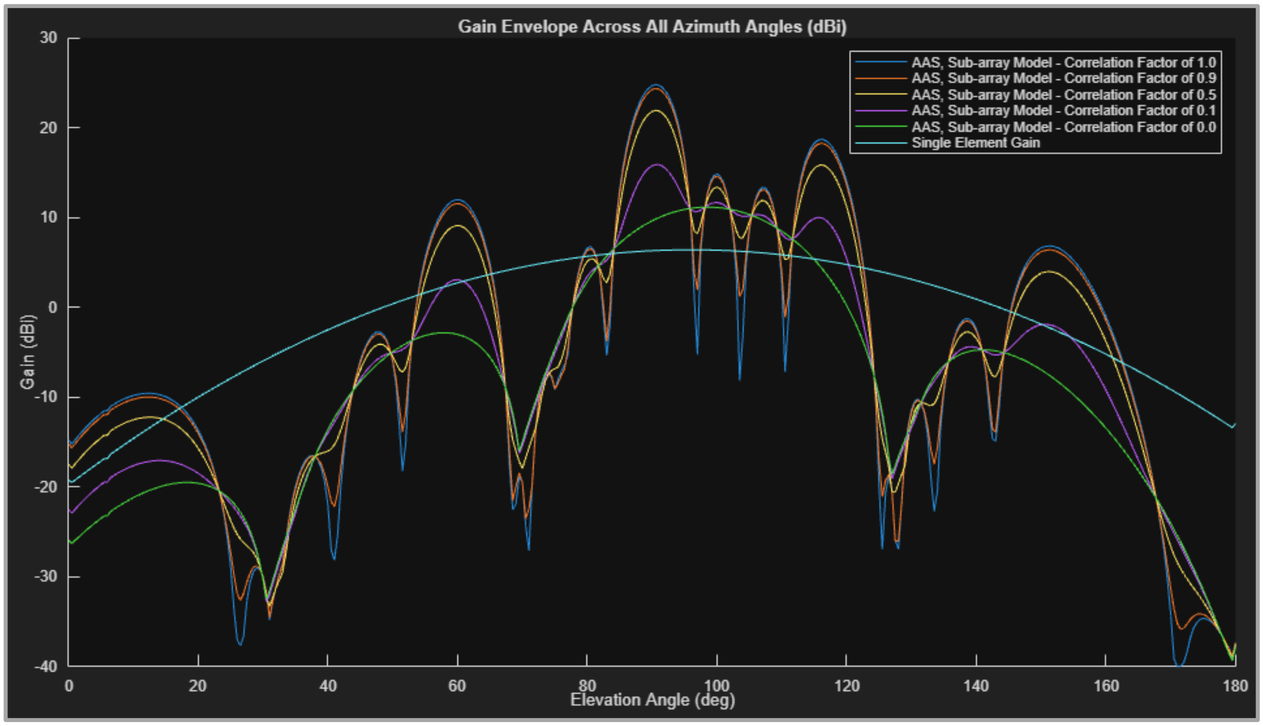

Figure 9: Overlay of Gain Envelope Plots (Steered to the Horizon)

## 5. ADDITIONAL FINDINGS

### 5.1 Commercially Available AAS

5.1.1 There are multiple cases in which commercially deployed AAS configurations differ from the typical ITU-R parameters.

5.1.2 For example, the Ericsson AIR 6494 Model specifies 64 transmit/receive chains and a total of 256 radiating elements.[5] Assuming dual polarization, this implies there are 128 elements per polarization. Given 64 transceiver chains and 256 radiation elements, it can be inferred that each chain consists of 4 radiating elements or 2 elements per polarization.

5.1.3 While detailed array geometry is not provided in the specification overview, one configuration that consistent with the parameters described in section 5.1.2 would be an 8 by 8 grid of sub-arrays where each sub-array comprises two vertically stacked elements per polarization. This configuration (e.g., 8 × 8 × 2 × 2) differs from the typical ITU-R representative model (e.g., 4 × 8 × 3 × 2), illustrating that commercially deployed AAS products may employ different sub-array sizes and element groupings.

### 5.2 ITU-R Liaison Statements

5.2.1 In June of 2021, a liaison statement from the ITU-R Director of the Radiocommunication Bureau on behalf of the 3rd Generation Partnership Project (3GPP) TSG RAN responded to questions raised by Working Party 1C regarding test methods for over-the-air TRP field measurements of unwanted emissions from IMT radio equipment utilizing AAS.[6] A relevant yet seemingly unexplored claim was made and is quoted below.

*5.2.2 "The radiating characteristics for a specific frequency vary as a function of the signal correlation applied to the array antenna and the frequency characteristics related to the radiating element. For unwanted emissions, the correlation is undetermined and varies as function of the emissions relationship to the wanted signal but will depend strongly on and vary based on antenna configuration and implementation. Consequently, a test signal in itself does not guarantee accurate measurement of unwanted emissions in the field."*

5.2.3 It is unclear if further guidance was provided on the undetermined nature of unwanted emissions, nevertheless the problem was clearly identified by 3GPP to ITU-R.

### 5.3 3GPP Developments

5.3.1 ITU-R Resolution 256 of WRC-23 initiated the study of sharing and compatibility studies between proposed IMT in the bands 4400 to 4800 MHz, 7125 to 8400 MHz and 14800 to 15350 MHz with existing services in and adjacent to these bands. [7]

5.3.2 In support of this effort, 3GPP is developing a technical report which upon other factors, provides additional considerations for modelling the array antenna gain outside the carrier.[8] In its explanation

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[5] See Ericsson AIR 6494 Model specification overview available at: https://www.ericsson.com/en/portfolio/networks/ericsson-radio-system/radio/macro/massive-mimo/air-6494

[6] See liaison statement at page 2, available at: https://www.itu.int/md/R19-WP1C-C-0073/en

[7] See Res.256 (WRC-23) (ex.COM6/26) *resolves* at page 395, available at: https://www.itu.int/en/ITU-R/study-groups/rcpm/Pages/wrc-27-studies.aspx

[8] See 3GPP TR 38.922 section 7.3, available at: https://www.etsi.org/deliver/etsi_tr/138900_138999/138922/19.03.00_60/tr_138922v190300p.pdf

of modelling assumptions it provides an update to the composite radiation gain pattern equation by applying a correlation factor as a function of frequency. The correlation factor, denoted as $\rho$, is frequency dependent.

5.3.3 For informative purposes, the visual model provided in 3GPP TR 38.922 is extracted and reproduced below in Figure 10.

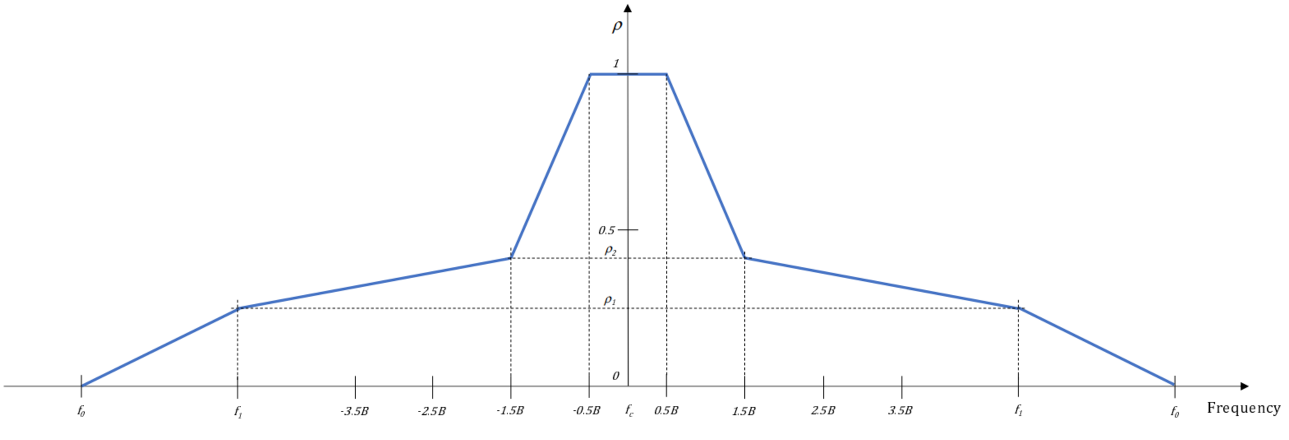

**Figure 7.3.2.1.2-1: Array correlation factor roll-off model.**

**Figure 10: Reproduced Figure from 3GPP TR 38.922 - Correlation as a Function of Frequency**

## 5.4 Institutional Research

5.4.1 Technical researchers have recognized the need for better characterization of AAS modelling in the unwanted domain. A study conducted by Rizk, Christ; Seguenot, Eric; Kaltenberger, Florian; Nussbaum, Dominique; Moro, Andrea; Sinicco, Alessandro; and Arora, Sagar, titled *Actual out-of-band emissions from massive MIMO antennas* published in late 2025, recognized that "characteristics of unwanted emissions arising from nonlinear hardware effects such as PA distortions remain less explored," and that these emissions can "pose significant challenges in meeting regulatory spectral masks and in minimizing adjacent channel interference." [9]

5.4.2 The above-mentioned research group performed theoretical calculations and assessed radiated measurements to better characterize unwanted emissions of AAS. Key conclusions made are quoted below:

*5.4.3 "In the linear regime with DPD enabled, OOB components across subarrays are decorrelated, resulting in incoherent radiation and improved adjacent channel leakage ratio (ACLR). Conversely, in the nonlinear regime without DPD, OOB emissions become spatially coherent and are beamformed in the same direction as the desired signal, leading to an increased risk of interference. … While this study focused on the n78 band (3.4–3.8 GHz), the observed spatial characteristics of OOB emissions are fundamentally governed by array configuration, PA nonlinearity, and signal correlation factors that remain relevant across frequency bands."*

5.4.4 Several results from the study are reproduced below in Figures 11 and 12. One approach to consider when looking at these figures is that when the full array measurements (Blue) are significantly above the sub-array measurements (Red) this indicates that the signal is nearly fully correlated. When the full array is

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[9] See report available at: https://www.eurecom.fr/publication/8396

near the sub-array, there is less correlation. When the full array is below the sub-array, there is negative correlation.

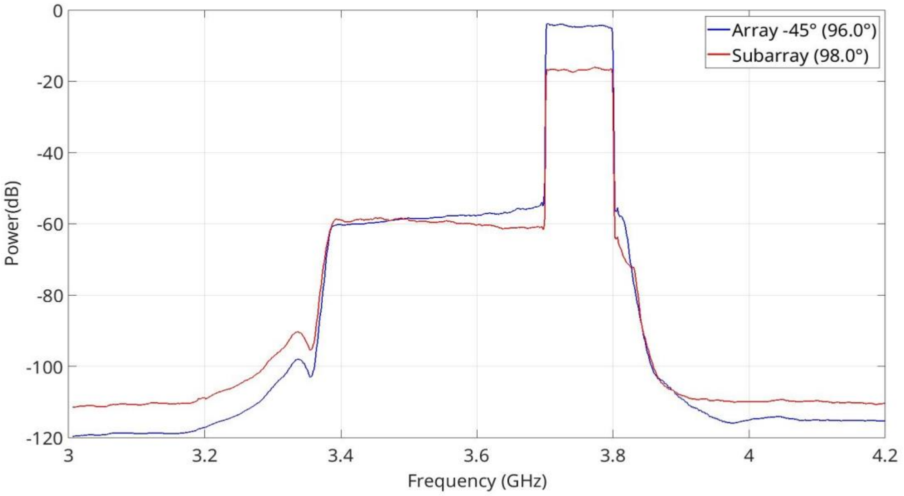

Fig. 6: Full antenna array spectrum compared to one subarray spectrum at bore sight with DPD in isopower mode

**Figure 11: Reproduced Figure from Rizk, Christ et al. Study – AAS Pattern With DPD**

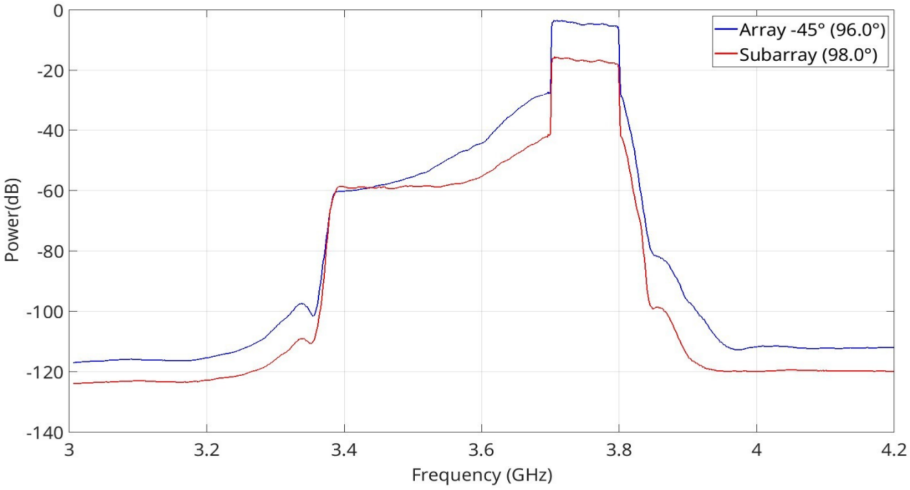

Fig. 7: Full antenna array spectrum compared to one subarray spectrum at bore sight without DPD in isopower mode

**Figure 12: Reproduced Figure from Rizk, Christ et al. Study – AAS Pattern Without DPD**

5.4.5 The above reproduced data clearly shows that, regardless the implementation, there remains some non-zero amount of signal correlation immediately adjacent to the wanted signal as well as for frequencies extending beyond immediately adjacent.

5.4.6 Furthermore, the researchers noted that the above reproduced results focus on boresight beamforming and that a detailed study of off-boresight effects is left for future work. Therefore, it is unclear if the findings and conclusions change for off-boresight directions.

## 6. **CONCLUSION**

6.1 AAS unwanted-emission antenna patterns are highly architecture-dependent and cannot be represented by a single fixed pattern. Current models do not yet sufficiently bound unwanted domain antenna gain, which can lead to inconsistent results between analyses. Current research further highlights the complexities involved in AAS radiation patterns in the unwanted domain. ICAO FSMP can play a valuable role through encouraging regulators, aviation and telecommunication alike, to carefully consider these complexities in safety critical interference assessments, to ensure protection of aeronautical systems.

— END —