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**Agenda item: 7.2.5**

**Source: CATT**

**Title: TP for other issues (Adjacent channel modelling)**

**Document for: Discussion**

# Introduction

This TP is to address the following concern from ITU-R WP5D:

|  |
| --- |
| *d ) IMT base station (inclusive of its AAS-related parameters) and IMT user equipment technical parameters for analyzing adjacent band compatibility of terrestrial IMT systems with other co-primary services in the ITU Radio Regulations.*  *WP 5D also seeks information about how the AAS performs in adjacent bands i.e. does its performance drops down to that of a single element or still some array features remain. If the latter is true how far in frequency should one assume the continuity of array features even with some degradation?* |

This TP consolidates the inputs to this meeting including R4-2417877, R4-2417546 and R4-2418395, and discussion outcomes under subclause 7.4.

# Text proposal

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# References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non‑specific.

- For a specific reference, subsequent revisions do not apply.

- For a non-specific reference, the latest version applies. In the case of a reference to a 3GPP document (including a GSM document), a non-specific reference implicitly refers to the latest version of that document *in the same Release as the present document*.

[1] 3GPP TR 21.905: "Vocabulary for 3GPP Specifications".

[2] RP-241326240787: “Study on IMT parameters for 4400 to 4800 MHz, 7125 to 8400 MHz and 14800 to 15350 MHz”, SID, FS\_NR\_IMT\_4400\_7125\_14800MHz, RAN#104. .

[3] R4-2400333: “Parameters of terrestrial component of IMT for sharing and compatibility studies in the frequency bands 4 400-4 800 MHz, 7 125-8 400 MHz and 14.8-15.35 GHz”, ITU-R WP 5D, LSin..

[4] R4-2410576: “LS on Parameters for 4400 to 4800 MHz of terrestrial component of IMT for sharing and compatibility studies in preparation for WRC-27”, RAN4#111, LSout

[5] R4-2414449: “LS Reply on Parameters for 7125 to 8400 MHz of terrestrial component of IMT for sharing and compatibility studies in preparation for WRC-27”, RAN4#112, LSout

[6] R4-24xxxxx: “LS Reply on Parameters for 14800 to 15350 MHz of terrestrial component of IMT for sharing and compatibility studies in preparation for WRC-27”, RAN4#xxx, LSout

[7] 3GPP TR 38.858: “Study on evolution of NR duplex operation”

[8] RP-241614: “Evolution of NR duplex operation: Sub-band full duplex (SBFD)”, WID, NR\_duplex\_evo, RAN#104

[9] 3GPP TS 38.104: “NR; Base Station (BS) radio transmission and reception”

[10] 3GPP TS 36.104: “Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception”

[11] 3GPP TS 38.101-3: “NR; User Equipment (UE) radio transmission and reception; Part 3: Range 1 and Range 2 Interworking operation with other radios”

[12] 3GPP TS 38.101-1: “NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone”

[13] ITU-R Recommendation SM.329: "Unwanted emissions in the spurious domain"

[14] 3GPP TR 38.921: “Study on International Mobile Telecommunications (IMT) parameters for 6.425 – 7.025 GHz, 7.025 – 7.125 GHz and 10.0. – 10.5 GHz”

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[17] Christopher Mollen, Ulf Gustavsson, Thomas Eriksson, Erik G Larsson, “Out of Band radiation Measure for MIMO arrays with beamformed transmission “, Proc. IEEE Int. Conf. Commun., May 2016.

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[19] E. Sienkiewicz, N. McGowan, B. Göransson, T. Chapman and T. Elfström, "Spatially dependent ACLR modelling," 2014 IEEE Conference on Antenna Measurements & Applications (CAMA), Antibes Juan-les-Pins, France, 2014, pp. 1-4,

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[21] C. Mollén, U. Gustavsson, T. Eriksson and E. G. Larsson, "Spatial Characteristics of Distortion Radiated From Antenna Arrays With Transceiver Nonlinearities," in IEEE Transactions on Wireless Communications, vol. 17, no. 10, pp. 6663-6679, Oct. 2018.

[22] Y. Zou et al., "Impact of Power Amplifier Nonlinearities in Multi-User Massive MIMO Downlink,” 2015 IEEE Globecom Workshops, San Diego, CA, USA, 2015, pp. 1-7.

[23] P Nandin et al, “Web Lab: A Web based set up for PA digital distortion and Characterisation”, IEEE Microwave Magazine, vol 16, no1, p 138- 140, Feb 2015

[24] TS 38 104, NR; Base Station (BS) radio transmission and reception.

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7.4 Modelling array antenna gain outside the carrier

### 7.4.1 General

7.4.1.1 Purpose

This clause aims to provide IMT base station and IMT user equipment techncial parameters for analyzing adjacent band compatibility of terrestrial IMT systems with other co-primary services in the ITU Radio Regulations covering aspects related to modelling array antenna gain outside the wanted carrier relevant for modelling spatial characteristics for unwanted emissions.

7.4.1.2 ITU radio regulations on adjacent terrestrial IMT systems with other co-primary services

There are adjacent services in the bands being considered for IMT 2030.

For example: for the case of 4400-4800 MHz, the adjacent band services are:

On the lower edge below 4400 MHz:

* Aeronautical radionavigation;
* Aeronautical mobile;
* Additional possible allocation of EESS (passive) as per Agenda Item 1.19 of WRC-27;

On the upper edge above 4800 MHz:

* Fixed service;
* Radio Astronomy;
* Radio navigation satellite;

For the case of 7125-8400 MHz, the adjacent band services are:

On the lower edge below 7125 MHz:

* Fixed
* Fixed Service Satellite (Earth-to-space)

On the upper edge above 8400 MHz:

* Space Research Service (space-to-Earth)
* Additional possible allocations of EESS (passive) as per Agenda Item 1.19 of WRC-27
* Earth Exploration Satellite
* Radiolocation
* Space Research (active).

For the case of 14.8-15.35 GHz, the adjacent band services are:

On the lower edge below 14.8 GHz:

* Fixed Service;
* Fixed Satellite Service (Earth-to-space)
* Radionavigation

On the upper edge above 15.35 GHz:

* Space research (passive)
* EESS (passive)
* Radio Astronomy

In particular, the frequency range 15.35 – 15.4 GHz is marked as a footnote 5.340 band, which is stating “*All Emissions are Prohibited*” with the exception of those provided by RR 5.511.

It is therefore important that out of band emissions are correctly modelled so that appropriate guidance is provided for the above question to WP 5D.

7.4.2 Adjacent channel modelling

7.4.2.1 Correlation roll-off based model

7.4.2.1.1 Modelling overview

The array antenna model adopted by 3GPP in TR 38.803 creates the composite pattern as a multiplication between the element factor (or sub-array element factor) and array factor. The array antenna model was first introduced in TR 37.840 in the early days of AAS for BS. Based on the antenna model, the average radiation pattern produced by an array antenna was evaluated and an analytical expression for the average radiation pattern was established.

The composite radiation gain pattern for pure LOS channel can be expressed in logarithmical scale as:

 (Eq. 7.4.1-1)

, where *r* is the correlation factor defined in the interval . Relevant parameter values for the frequency range 4400 to 4800 MHz can be found in subclause 4.4.1.2 and for 7125 to 8400 MHz in subclause 5.4.1.2, and for 14800 to 15350 MHz in subclause 6.5.1.2.

It can be noticed that the average antenna gain for the wanted signal where *r* is equal to 1, the composite array gain is produced (*GE,max* + 10log10(*Msub*) + 10log10(*MN*) dBi), while for unwanted emission away from the carrier where *r* is equal to 0 only the gain of the element/sub-array is produced (*GE,max* + 10log10(*Msub*) dBi). For sharing studies, it would be relevant to consider *r* being represented as a function of frequency.

 The impact of array signal correlation to directivity and gain response have been evaluated for different array antenna structures considered for 4400 to 4800 MHz, 7125 to 8400 MHz and 14800 to 15350 MHz considering 10 degrees down-tilt beam steering direction. The results are plotted in Figure 7.4.1-1.

 

Figure 7.4.1-1: Vertical radiation pattern considering different array geometries and correlation factor.

The array factor impact due decorrelation can be analysed for all antenna geometries separately. The array factor drops gradually for low correlation as shown in Figure 7.4.1-2.



Figure 7.4.1-2: Array factor decorrelation characteristics plotted as function of correlation.

It can be noticed that the average gain drops gradually when the array correlation reduces. At array correlation 0.5 the array factor has reduced approximately 3 dB.

The characteristic is visualised in Figure 7.4.1-2 can be used to translate measured directivity drop to correlation factors to use for modelling purposes.

7.4.2.1.2 Correlation roll-off model

Since the array factor gain relies on coherent combining of signals it is not expected that the array factor will operate outside the carrier with full strength in situations outside the carrier where the emission is created as the sum of correlated intermodulation distortion and uncorrelated wide band noise. The Inter-Modulation Distortion (IMD) is coming from non-linear transmitter. The characteristics is typically categorized as distortions due third order (IM3), fifth order (IM5), seven order (IM7), etc. IMD. It is known that the order of IMD will determine the spectral distribution of the distortion. The IMD will also depend on the wanted signal carrier bandwidth, *B*. The IMD response typically reduces moving away from the edge of the wanted signal.

For the wanted carrier (within the interval , *fc* is the carrier centre frequency) full array factor is expected which means that the correlation factor is equal to 1. Moving away from the carrier edge () the correlation will drop gradually due to the composition of the emission outside the carrier. The emission will be created as the sum of correlated noise due to intermodulation products and non-correlated noise due to wideband transmitter noise. The relation to the induvial noise levels will determine the out-of-carrier correlation properties in the adjacent emission regions. At a certain frequency offset to the carrier edge the emission noise will be dominated by wideband noise which means that the correlation is equal to 0.

Therefore, it would be appropriate to define a model for the array correlation factor to account for carrier bandwidth and decaying correlation moving away from the carrier edge.

To properly model the AAS base station array antenna gain pattern outside the carrier the correlation factor needs to be modelled as a function of frequency offset to the carrier centre frequency. To capture fundamental aspects of the array antenna gain drop outside the wanted signal a parameterized piece-wise linear roll-off model can be adopted for the correlation factor, as visualised in Figure 7.4.2-1.

 

Figure 7.4.2-1: Array correlation factor roll-off model.

The roll-off is modelled to reduce stepwise moving away from the centre frequency, also the characteristics is assumed to be symmetrical around the wanted carrier. Close to the carrier the correlation is expected to be close to 1, while moving towards *+/-1.5B* reducing to *r2*. At *f1* the corelation have reduced even more to *r1*. At *f0* the correlation has reduced to 0, which corresponds to that the array factor gain in 0 dB.

For this model to be use-full parameter values for *B*, *f0*, *f1*, *r1* and *r2* needs to be determined.

Using the approach above the antenna model can be extended to capture array antenna gain outside the wanted carrier as:

 (Eq. 7.4.2-1)

Observe that the extended array antenna model only captures effect due to array signal correlation and not effects due to antenna element detuning effects of mismatch effects in transmission lines and Radio Distribution Network (RDN).

Observe that the array correlation roll-off model presented above only captures decorrelation effects related to the array factor. Keep in mind that even though the array factor totally collapses the sub-array still produce gain far outside the carrier. Typically, the sub-array starts to collapse outside the operating band until the antenna is completely detuned far from the centre of the operating band.

Another aspect to consider when modelling spatial unwanted emission outside the carrier is the suppression of unwanted emission outside the carrier in the adjacent channel regions as well as in the spurious domain. In these regions the emission is suppressed by the ACLR and RF filter suppression.

The radiated emission from a base station to be studied in a sharing situation can be calculated as:

, where *Ptx* is the power fed to the antenna, *f* is the frequency offset between the carrier centre frequency and the considered frequency. The frequency dependence for the gain pattern *AA(q,j,f)* as described in Eq. 7.4.2-1.

The power fed to the antenna can be expressed as a function of frequency offset as:

, where is *P* is the carrier power, *S(f)* is the suppression achieved by *ACLR1* (First adjacent channel), *ACLR2* (Second adjacent channel), *ACLR3* (Third adjacent channel) and additional RF filter suppression (if frequencies outside the operating band is considered) as function frequency offset.

It is evident that the radiated power in the adjacent channel regions depends on the drop of antenna gain and the power fed to the antenna. The combined effect should be considered to properly model sharing situations.

7.4.2.2 Array ACLR based model

7.4.2.2.1 Overview

Out of band emissions are well understood but often for a single transmitter.

It is necessary to distinguish between a *single element ACLR*, and an *array ACLR*. In a non AAS system, where the radiation pattern is “constant” over a sector, the single element ACLR makes sense, since the received power ratio at any point is the same as the transmitted. However, with AAS, the desired signal experiences also an array/beamforming gain that might be different from the array/beamforming gain of the interfering signal received in the adjacent band; this later observation is also dependent if SU or MU MIMO is used (ie the array may send distortions in unintended directions).

When an array in AAS base stations is used, the 3GPP specifications provide a method to compute the array ACLR (albeit in a TRP mode) [24]:

*“The ACLR (CACLR) absolute basic limits in table 6.6.3.2-2 + X, 6.6.3.2-2a + X (where X = 9 dB) or the ACLR (CACLR) basic limit in table 6.6.3.2-1, 6.6.3.2-2a or 6.6.3.2-3, whichever is less stringent, shall apply.”*

However, the above method is array pattern agnostic and does not account for beamforming variations due to MU MIMO.

Recent published results, discussed/summarized in this report, show that that array ACLR is spatially sensitive and is also dependent if SU or MU MIMO functionality is utilized. There is thus a need to accurately model the ACLR when AAS is used.

*As part of additional information requested by ITU-R WP 5D establish a model for array correlation factor (r) roll-off to describe how the array factor collapses moving away from the centre frequency. If the beamforming performance degrades towards a single element radiation pattern, then the frequency when the continuity of array features is regarded as degraded, will also need to be determined.*

To address the SI, the questions posed may be devolved into topics below:

1. Establish a model for array correlation factor-ie the correlation of the in-band signal with the out of band signal.

There is no definition of an array correlation factor. Is it the correlation of the in-band signal with out of band signal. But the in-band signal, Pinband (θ,φ), is spatially sensitive and as discussed below the out of band signal , P oob (θ,φ), may also be spatially sensitive. Then the array correlation ** is also spatially sensitive may be defined as:

*r (θ,* φ) *=* E (Pinband (θ,φ) PT oob (θ,φ) ) ………………………….(6)

1. How does the array factor collapse when moving away from the centre frequency?

This also means that *r (θ,* φ) defined above is a function of frequency separation from the band centre. In this case best to denote this as:

*rΔ* f*(θ,* φ)………………………………………………………………..(7)

Where Δf is the frequency separation from band centre

1. If the beamforming performance degrades towards a single element radiation pattern, then the frequency when the continuity of array features is regarded as degraded, will also need to be determined.

Therefore we would need to characterise and investigate the constituent components of P oob (θ,φ) as a function of Δf

The above topics are interrelated but need to be separately discussed as well. The discussion below addresses topics 2 and 3 respectively.

Array performance in adjacent bands is governed by:

* Array performance at different frequencies arising due to adjacent bands.
* Modelling of the impact of PA non linearities
* Modelling of band pass filters
* Putting all of the above together to obtain an end-to-end model

Additionally, one must also consider if the array is supporting a single user or multi-user systems.

7.4.2.2.2 Array performance at adjacent band frequencies

Assume that the lower and upper adjacent bands have a bandwidth of 100 MHz each respectively. Arrays in a band are designed at the centre frequency of a given band ie vertical and horizontal spacing is determined by the centre frequency of the band which for example in band 1 is 4600 MHz shown in Table 7.4.2.2.2-1 below. Likewise for other bands. The lower and upper adjacent bands can be simulated via a proxy array with different spacings e.g for band 1, the lower adjacent band is 4300-4400 MHz with centre frequency 4350 MHz. Therefore, for band 1, changing the vertical spacing to 0.74 lambda and horizontal spacing to 0.53 lambda will effectively simulate the lower adjacent band. Likewise for the upper adjacent band (0.66, 0.474) will simulate the upper adjacent band.

**Table 7.4.2.2.2-1: Array performance in adjacent bands**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Band** | **Centre Frequency** | **0.7 Lambda, 0.5 Lambda****(cm)** | **Centre freq of Lower adj band** | **Centre freq of Upper adj band** | **0.7 Lambda, 0.5 Lambda for lower adj band** | **0.7 Lambda, 0.5 Lambda for upper adj band** |
| 1 | 4600 MHz | 4.565/3.26 | 4350 MHz  | 4850 MHz | 4.827/3.45(0.74, 0.53) | 4.33/3.09(0.66, 0.474) |
| 2 | 7762.5 MHz | 2.7/1.93 | 7075 MHz | 8450 MHz | 2.96/2.118(0.767, 0.55) | 2.48/1.773(0.64, 0.46) |
| 3 | 15.075 GHz | 1.39/0.99 | 14.75 GHz | 15.40 GHz | 1.42/1.012(0.715, 0.511) | 1.36/0.97(0.68, 0.49) |

The following parameter/metrics are impacted [15] when the inter element spacing is changed:

* Nulls
* Maxima
* Half power points
* Minor lobe maxima
* First null beamwidth
* Half power beamwidth
* First side lobe beamwidth

Exact expressions for the above are given below from [15] for a ULA along the z axis and for omni directional antennas. Considering the exact formulas below in Table 7.4.2.2.2-2 and Table 7.4.2.2.2-3 the changes due to inter element spacing in the proxy array will result in some changes to the values of the above metrics. See Figure 7.4.2.2.2-1, Figure 7.4.2.2.2-2 and Figure 7.4.2.2.2-3 for an eight element ULA for 0.5 lambda, 0.7 lambda and 0.8 lambda inter element spacing respectively. However these frequency/wavelength adjustments are no different to what is present today in systems that have a wide operating bandwidth and antennas are designed at the centre frequency of the band). Note that the results below are not for an array of sub arrays and 3GPP antenna element patterns, but the trends will be similar for the array of sub array case as well.

**Table 7.4.2.2.2-2: Broadside array antenna pattern equations**

|  |
| --- |
| **Nulls, Maxima, Half-Power points and Minor Lobe maxima for Broadside Arrays** |
| Nulls  | θn = cos-1 (), n = 1,2,3….,  |
| Maxima  | θm = cos-1 (), m = 0,1,2,3….,  |
| Half Power Points  | θh = cos-1 (),  |
| Minor Lobe Maxima | θs= cos-1 (), s = 1,2,3,  |

**Table 7.4.2.2.2-3: Broadside array beamwidth equations**

|  |
| --- |
| **Beamwidths for Uniform Amplitude Broadside Arrays** |
| First Null beamwidth (FNBW) | n= |
| Half Power beamwidth (HPBW) | h  |
| First sidelobe beamwidth (FSLBW) |   |



**Figure 7.4.2.2.2-1: Eight element ULA response with 0.5 lambda spacing**



**Figure 7.4.2.2.2-2: Eight element ULA response with 0.7 lambda spacing**



**Figure 7.4.2.2.2-3: Eight element ULA response with 0.8 lambda spacing**

It is also to be noted that in case of band 2 where the band is very wide (operating bandwidth 1275 MHz) proxy antenna inter element spacings for a carrier at the lower end of the band will almost have a similar impact as the lower adjacent band. Likewise for the upper end of the band.

The above inferences will also remain valid for the second adjacent band.

The above observations will remain valid even if the array is made of sub arrays and the notion that an array may drop down to a sub array in adjacent bands is not valid.

7.4.2.2.2 Modelling of PA non-linearities

Non linearities in hardware in the RF path cause signal distortions- both in band and out of band-(adjacent bands). The nonlinear components in the RF path consist of power amplifiers that are the main cause of nonlinear distortions but other components such as D/A converters, mixers, beam forming circuitry may also contribute to the nonlinear distortions. When antenna arrays are deployed, multiple users may be served by beam forming either in the analog domain or both in the analog and digital domain. Digital beamforming is commonly employed in today’s systems- such as zero forcing, MMSE [16]. This results in the placing of nulls in the path of all users except the desired user, but this operation may also cause out of band distortions to fall in unintended spatial directions.

The modelling of PA non linearities has received a lot of interest in the published literature [see 17,18-22 and references therein]. PA behavioural models can be classified as:

* Volterra series based,
* Artificial neural networks,
* Table look up methods,
* Models with linear and nonlinear memory, with and without memory etc.

Ref [17] gives a very good comparison of PA behavioural models in terms of metrics like identification complexity, adaptation complexity, running complexity etc. Measurements on some PAs and the accuracy of the models are presented in [20]. Some commonly used models use polynomials or memory polynomials [18,22], here PA units are modelled via 9th order polynomials whose coefficients are obtained from RF measurements. These papers conclude that the received signal with massive MIMO consists of a desired term with linear gain of the array and also a nonlinear distortion term. Additionally, if the linear response coefficients of the different parallel PAs (in the massive MIMO unit) are different (and they do have small differences), then even the linear signal terms are not fully coherently combining at the receiver. In case of the nonlinear distortion terms, this effect is even more evident as here the phase characteristics of the constituent terms representing the component PAs are different. These two effects manifest in the decrease of the desired instantaneous SINR. When pre-coded multiuser MIMO is used, [21,22] derive analytical models for three different precoder types and for each case derives the received signal. The later now consists of a linear useful signal part and several distortion terms arising from multiuser interference and nonlinear distortion. The conclusion of this paper is:

The choice of a PA behavioural model validated by measurements is needed. Ref [18,19] provide a good framework to model these non-linearities via polynomial models.

The differences in the linear responses of the parallel PAs have a large impact on the system performance. The nonlinear terms do not necessarily adopt the digital predistortion as easily and efficiently. Therefore, the impact of nonlinear power amplifiers is nontrivial both in band and out of band. However, to do this we would need a model for the differences in the PA models in an AAS.

Power Amplifier non linearities should be carefully modelled when considering adjacent channel impacts when MIMO arrays are used. The choice of a PA model should be agreed (say via polynomial models), then it may be validated by measurements and also agree on a model for the differences in the parameters for the distributed PAs.

We may assume for the sake of simplicity there are no differences in the PA model parameters in a distributed PA AAS.

Adjacent band impacts is however not the main focus of [18], but they are considered in [17,18,21]. These papers give the spatial distribution of out of band radiation in the presence of non-linear amplifiers that are modelled by orthogonal polynomials- a special case of the more general Volterra series as described in [17]. Refs [8,21] derive an expression for array ACLR when linear precoding is used with MIMO arrays and a spatial distribution of the ACLR is derived for 1, 2 and 10 users respectively. In particular, [21] develops a framework for rigorous analysis of the spatial characteristics of nonlinear distortion from arrays both in band and out of band. The framework is validated via measurements on a GaN class AB amplifier [23]. It is shown that in the immediate adjacent bands, the third order distortion terms are significant. For a two user MU MIMO case it is shown that the desired signal is beamformed in two directions but the adjacent band distortion signal (arising from PA non linearities) is not beamformed in the same direction as the desired signal. Consideration of this will be important in evaluating the impact of adjacent band victims due to PA non linearities in the operating band.

7.4.2.2.3 Modelling of band pass filters

The filters modelled in some references [15,] use a root raised cosine filter with an excess bandwidth of 0.22. Also, the adjacent channel has the same bandwidth as the operating bandwidth. This is clearly not the case, for all the bands under consideration the operating bandwidths are much larger than the carrier bandwidth. The adjacent channel bandwidth may be say 100 MHz. However, the framework in [23] can be used to change the bandwidth of the BPF to reflect the operating bandwidth. However, we must specify the bandwidth of the BPF and a model for the BPF.

< End of change>