Out-of-Band Interference in 5G mmW Multi-Antenna Transceivers: Co-existence Scenarios

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***Abstract*—Large antenna arrays used for compensating the millimeter wave (mmW) path loss gives interesting perspectives for considering out-of-band emissions and reception signals to be direction dependent. In addition, co-existence of lower frequency and mmW systems set special requirements for both conventional cellular and mmW systems. This paper presents discussion on these two cases as the most important out-of-band interference scenarios in fifth generation systems. Effects of intermodulation and adjacent channel leakage are discussed in both mmW beamforming transceiver and receiver, respectively. It is concluded that distortion is behaving differently in multi-antenna transmitter than at the receiver. Over-the-Air (OTA) measured and simulated examples of the nonlinear behavior of an array are given for receiver and transmitter, respectively. Furthermore, smart array linearization scheme given as a reference provides new perspective to consider the direction dependent out-of-band distortion as a part of the future cellular standards.**

Keywords*—ACLR, Arrays, Co-existence, Intermodulation, 3GPP, 5G.

I. INTRODUCTION

One of the key drivers for the development of the next generation of communication systems, mostly referred as fifth generation (5G), is the envisioned ten-folded data rates compared with the current Long Term Evolution (LTE) (20 Gbps and 10 Gbps peak rates for downlink and uplink, respectively). One of the first 5G proof of concept mmW wireless backhaul system was showcased during the 2018 Winter Olympic Games in Korea and it was developed in 5GChampion project [1]. First third generation partnership project (3GPP) standards for 5G have been released at end of the 2017 and those include new radio (NR) interface requirements for both currently used frequencies and millimeter wave frequency bands [2]. The first commercial implementation of the 5G mmW system will be based on non-standalone architecture, which leverage the LTE and NR air interfaces and current LTE core network. The first network deployments are expected early 2019 [3].

The large variety of operational frequency bands of cellular and other wireless systems, and combinations of those, will increase significantly with new 3GPP standard releases. Aggregated combinations of conventional sub-6 GHz and mmW bands are necessary for successful and reliable communications in different propagation environments and user scenarios. Hence, the co-existence requirement of the different frequency bands appear even within the same radio unit. The first 3GPP 5G NR standard [2] includes some requirements for the interoperability between RF bands. However, not all combinations have been identified and the discussion on the requirements is still ongoing. One of the unspecified interference scenarios is the co-existence of 5G mmW and LTE LAA (Licensed Assisted Access) systems. Whereas the lower mmW bands are specified around 28 GHz, the operational band for LTE LAA is between 5 and 6 GHz. The 5 GHz band Wi-Fi, based on IEEE 802.11 standards, shares the same operational frequency band with LTE LAA. The 5 GHz Wi-Fi and LTE LAA radios may generate spurious harmonics to the 5G mmW band causing interoperability problems. These harmonics may desensitize the 5G mmW receiver. Moreover, many of the devices designed for sub-6 GHz frequencies have not been strictly specified and measured in the presence of co-located mmW systems. A large dynamic between path losses of currently used sub-6 GHz and mmW frequencies arises a scenario where the interfering lower frequency system might have significant transmission power compared with received mmW signal. A multi-radio interoperability between different wireless systems has not formally standardized in the 3GPP standard or by any other standardization body. Furthermore, it is not widely understood how mmW beamforming receiver and transmitter treats the out-of-band emissions and spurious responses in practice.

The 5G mmW radio signals face higher path loss than lower frequency LTE signals. Both transmission and reception devices will use MIMO (multiple input multiple output) antenna arrays to improve the radiated transmission and reception performance. The transmission (TX) and reception (RX) beams may be narrowed to improve the coverage and to reduce the radio interference from unwanted directions [4]. Moreover, adaptive beam forming will be used to direct radiated signals dynamically to the optimal direction. For example, a base station can dynamically follow the movement of the user. The radiated spectral mask of the antenna array is required to fulfill the 3GPP out-of-band emission specification. This requirement is either a conductive or a radiated requirement based on the base station type [2]. Conductive requirements are straightforward to characterize and measure. However, radiated out-of-band interference includes the effects of antenna array, thus the distortion becomes as direction dependent figure of merit. Especially, if parallel nonlinearities over the array have differences with each other, the beam pattern of the nonlinearity may differ from the beam pattern of the linear signal [5].

Radio performance requirements for previous generation for 3GPP standards GSM (Global System for Mobile Communications), WCDMA (Wideband Code Division Multiplexing Access) and LTE have been specified with conducted measurements, only. The 5G NR standard below 6

GHz has conductive radio requirements but for mmW bands radio performance is specified with OTA, only [2]. Accurate OTA power measurements at mmW frequencies require new measurement methods compared to previous 3GPP standards. Thus, the accuracy of the OTA measurements at mmW frequencies is an important topic in standardization and in academia.

In this paper, we focus on discussing the two different interoperability scenarios, which are: (1) mmW system co-existing with an interfering Wi-Fi or LTE LAA system and (2) Two co-located 5G mmW systems operating at adjacent channels with respect to each other. Several other co-existence and interference scenarios are present in 5G systems, but these two are considered to have significant meaning from the standardization perspective.

The rest of the paper is organized as follows. Interference scenarios are studied in Section II. First interference scenario is between 5G mmW and Wi-Fi/LTE LAA is presented. Then out-of-band interference of 5G mmW transmitter is studied with simulations. The out-of-band interference of 5G mmW receiver is studied and linearity measurement results of proof-of-concept receiver are shown. Finally, the conclusions based on the analysis are drawn.

II. INTEROPERABILITY SCENARIOS

Radio interoperability is a multi-dimensional optimization topic. There is no a single solution to guarantee that multiple radios operating at different frequency bands can co-exist without interference. The radio interoperability can be defined, for example, with a spectrum consumption model, which is described in IEEE standard 1900.5.2 [6]. The spectrum model includes following parameters that define radio interoperability:

- Conducted transmission power
- Spectrum mask of transmission and reception signals
- Antenna directivity
- Propagation loss model
- Reception intermodulation signal mask
- Transmission and reception timings
- Location and transmission starting time

The spectrum model above is a generic model for the radio interoperability where all aspects of the radio transmission and reception are taken into account. In our studied interference scenarios, the interfering and the victim radios are near vicinity of each other.

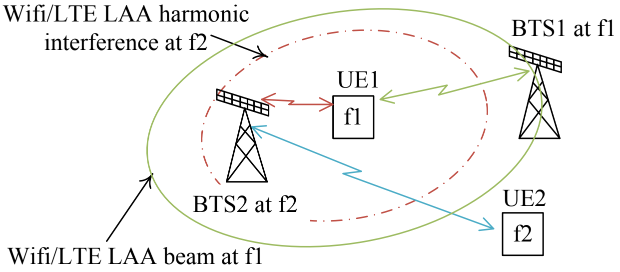


Fig. 1. Wi-Fi/LTE LAA harmonic interference scenario to 5G mmW.

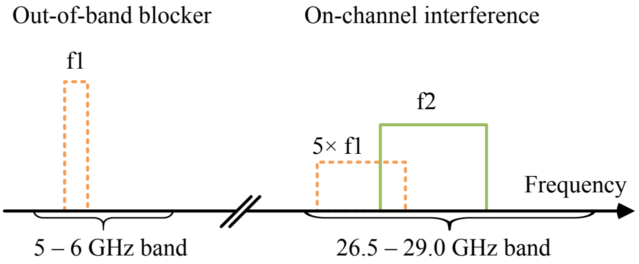


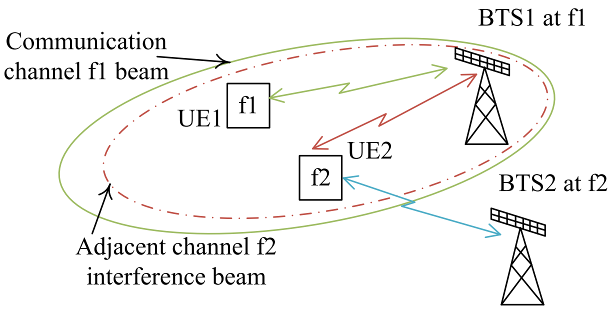
Fig. 2. Wi-Fi/LTE LAA band interference scenarios to 5G mmW band.

A. 5G mmW and LTE LAA / Wi-Fi interference

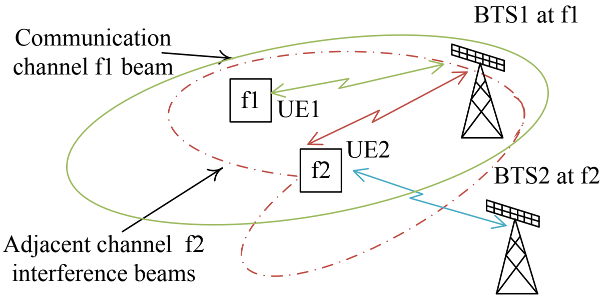
It is assumed here that the 5G mmW, Wi-Fi and LTE LAA systems will be deployed at the same indoor locations and these networks will overlay each other. This is a viable scenario as all these three systems may be implemented into one base station unit in order to provide full flexibility for the operators for network deployment. In some deployment scenarios, all these three systems need to operate simultaneously. An illustration of the network deployment scenario is shown in Fig. 1. The 5G mmW base station (BTS2) and user equipment 2 (UE) operate at mmW frequency of f2 and Wi-Fi/LTE LAA UE1 and BTS1 operate at frequency of f1. The UE1 generates harmonic interference at f2 frequency overlapping the wanted signal and desensitizing the 5G mmW receiver, as illustrated in Fig. 2. This scenario happens when Wi-Fi or LTE LAA terminal operates at close proximity of 5G mmW BTS. For example, the 5G mmW BTS is installed to ceiling of the corridor and user is uploading content via Wi-Fi/LTE LAA network located in close proximity of the 5G BTS.

The Wi-Fi/LTE LAA transmission itself is an out-of-band blocker for 5G mmW receiver and it may be at high level in the mmW antenna and receiver due to smaller path loss than mmW signal. Linearity of the 5G mmW receiver needs to tolerate, not only mmW band interference, but Wi-Fi/LTE LAA out-of-band blocker, as well. Maximum effective radiated isotropic power (EIRP) of Wi-Fi UE at 5GHz band is in USA +24dBm and in Europe +20dBm and the maximum conducted LTE LAA UE power is +23 dBm. The Wi-Fi/LAA blocker level may be close to 3GPP LTE out-of-band requirement -15dBm [2] in real life installation since at least 40 centimeter the guard distance is needed between radios. The 5G mmW receiver can be implemented without pre-selection antenna filter and thus only filtering is coming from the frequency response of the antenna before non-linear amplifiers. RF architecture without dedicated RF band selection filter is used in [1] and expected to common approach to avoid lossy and large filtering elements at mmW frequencies.

The fifth harmonic of the LTE LAA or Wi-Fi transmission will generate harmonic interference falling to 28 GHz band as shown in Fig. 2. The 5th harmonic interference of the Wi-Fi/LTE LAA transmission is five times wider than the communication transmission. For example, if LTE signal is 20 MHz wide, the 5th harmonic is 100 MHz which is in the same range to the 5G



(a) Adjacent channel interference without directive array linearization



(b) Adjacent channel interference in 5G mmW system with array linearization

Fig. 3. Adjacent channel TX interference scenarios of 5G mmW array.

mmW signal bandwidth. The Wi-Fi transmission may be up to 160 MHz wide and the harmonic spurious is up to 800 MHz, which is wider than currently standardized 5G mmW signal bandwidth of 400 MHz [2]. Current 3GPP LTE LAA standard for band 46 for UE specifies that the interference transmission up to 26 GHz needs to be below –30dBm @ 1 MHz or –17dBm @ 20 MHz [7]. This requirement is not covering the whole 5G mmW frequency band and the specified harmonic power is significantly higher than not yet specified reference sensitivity level of 5G NR mmW receiver. Actual power levels of harmonics transmissions is mainly caused by the power amplifier (PA) and the operation class of it. The class A power amplifier produces lower harmonics as class AB or class C devices. The drawback of more linear operation of PA is the current consumption. For example, the proof-of-concept 5G mmW receiver has receiver sensitivity –56 dBm without antenna gains [1].

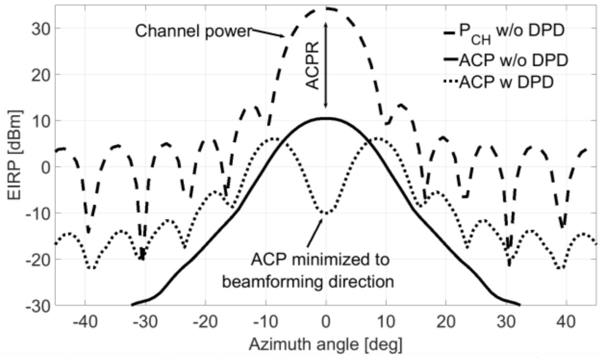


Fig. 4. Directivity effect of array linearization to TX ACLR performance.

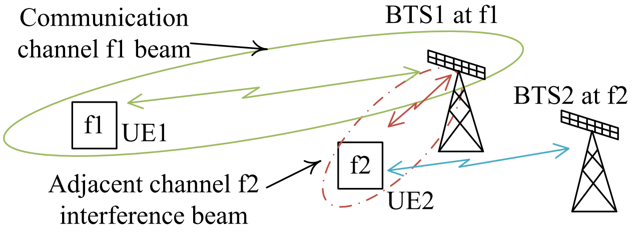


Fig. 5. Adjacent channel interference in receiver due to other 5G mmW band transmission.

The multi-radio interoperability can be done with physical separation. A needed guard distance between interfering and the victim radios depends on the interfering signal power level, the sensitivity of the receiver, antenna gains and the allowed sensitivity reduction of the receiver. This interference scenario may occur between radios within in the same multi-radio unit operating simultaneously. A sufficient antenna isolation between transmission and reception antennas is needed to ensure multi-radio interoperability.

B. 5G mmW transmitter generated interference

The transmission spectrum mask of the 3GPP 5G NR transmission is defined for the mmW base station transmitter with OTA measurement [2]. According to the standard, the TX ACLR (Adjacent Channel Leakage Ratio) requirement is defined as TRP (Total Radiated Power), where the transmission power is integrated over the whole space. The TX ACLR requirement for 5G mmW bands is shown in Table I. These requirements are reduced from the LTE band requirement of –45 dB due to higher frequency and more demanding radio implementation. The ACLR is measured with OTA and the requirement is valid for the whole array.

Two adjacent channel transmission interference scenarios are illustrated in Fig. 3a and 3b. The Fig. 3a illustrates a case where the adjacent transmission channel power covers similar shape area than communication signal transmission. This happens when a single antenna (e.g. LTE system) or mmW antenna array without array linearization is used. The Fig. 3b illustrates a case where the adjacent transmission channel power has a different coverage than the communication signal. This case occurs with mmW antenna array with array linearization [5].

When discussing about array ACLR, we should keep in mind that an antenna array fundamentally only directs the power. Hence, the TRP ACLR (or absolute ACP (Adjacent Channel Power) is independent on the intended transmission direction. However, as it has been shown and discussed in [5], [8]-[12], the ACP may, in some cases, experience the array response differently than the fundamental signal. Such behavior can appear when multiple parallel nonlinear array elements (e.g. multiple PAs each driving one antenna element) has different shapes of nonlinearity or they are driven with different

TABLE I. OTA ACLR REQUIREMENT FOR 5G MMW RADIO

Frequency band	**24.24 – 33.4 GHz**	**37 – 52.6 GHz**
ACLR TX requirement	–28.0 dB	–26.0 dB

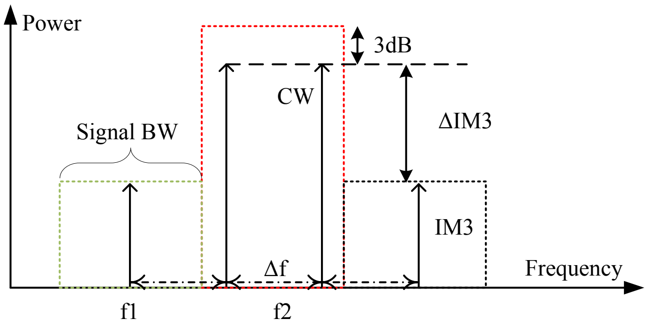


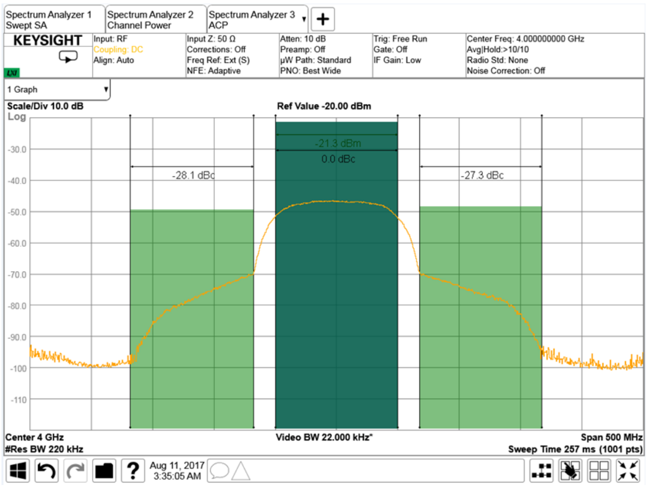
Fig. 6. Third order IMD measurement with CW and modulated signal.

amplitude levels. With directive array linearization schemes presented e.g. in [5], the differences can be even used to shape the beam of the ACP with respect to the fundamental signal. Similar effect of ACP spreading may happen also when multiple independent data signals (i.e. multiple streams) are transmitted from the same array such as shown in [5],[10]-[12]. However, without the differences between the nonlinearities of the parallel antenna branches, this effect does not happen in single-stream transmission.

An example of directive ACP is presented in Fig. 4. The figure demonstrates the channel and adjacent channel powers over the azimuth angle with and without a directive digital predistortion (DPD) scheme. The details of the linearization concept and the analysis flow resulting the directed ACP is presented in [5]. In this example, the ACLR observed in beamforming direction is with and without DPD is –44 dB and –23 dB. However, corresponding ACLR values characterized as TRP are –25 dB and –22 dB, with and without DPD, respectively. Hence, TX ACLR is directive, if differences over the parallel nonlinearities are utilized for linearization. TRP ACP specification does not necessarily guarantee the interference level between the two systems if the directivity is not taken into account in specifications.

C. *Adjacent channel interference to 5G mmW receiver*

The mmW receiver will face similar near-far problems than any other cellular receiver and this scenario is illustrated in Fig. 5. The victim mmW receiver e.g. BTS1 operates at frequency f1 and it communicates to UE1, which is at the edge of the cell. A UE2 connected to the BTS2 operates at frequency f2 nearby of the BTS1. When BTS1 receivers a weak signal at frequency f1, simultaneously it receives a strong interference at the adjacent radio channel f2. The spectrum of the strong interference signal at f2 may spectrally grow over to the frequency f1 due to non-linearities of the receiver. Thus, the spectral regrowth deteriorates the quality of the received signal.



Input: RF
Coupling: DC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Ext (S)
NFE: Adaptive
Atten: 10 dB
Preamp: Off
µW Path: Standard
PNO: Best Wide
Trig: Free Run
Gate: Off
IF Gain: Low
Center Freq: 4.000000000 GHz
Avg|Hold:>10/10
Radio Std: None
Noise Correction: Off
Scale/Div 10.0 dB
Ref Value -20.00 dBm
Center 4 GHz
#Res BW 220 kHz
Video BW 22.000 kHz*
Span 500 MHz
Sweep Time 257 ms (1001 pts)

Fig. 7. Measured spectrum of received signal, RX ACP clearly visible.

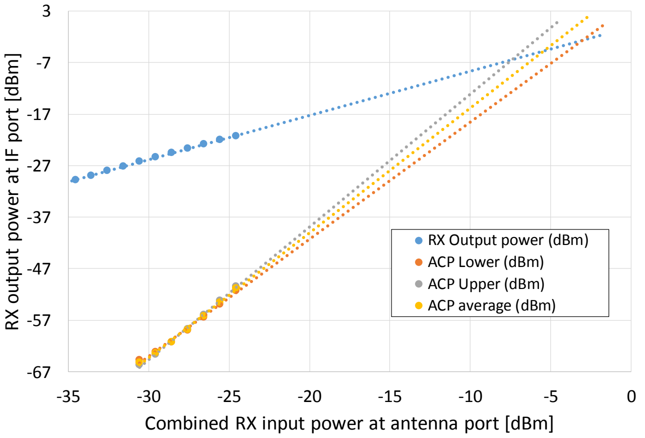


Fig. 8. Linearity measurement of array receiver to main beam direction.

The linearity of the receiver determines how strong interference the receiver can tolerate. When multiple signals interact in a non-linear component, a mixing process will generate new frequency components from the received signals. One of the most commonly used a merit of linearity of the receiver is the third-order intercept point (IP3) [13]. The third-order linearity can be measured with a two-tone test, which is shown in Fig. 6. Two CW (Continuous Wave) signals are fed into the receiver and mixing products Δf frequency apart from the test signals is measured. This two-tone measurement method is used for linearity measurement of array receiver in [14]. The input IP3 point (IIP3) can be calculated [13]

$$IIP3 = \frac{1}{2(\Delta IM3)} + P_{tone} \qquad (1)$$

where P_{tone} is the power of one CW test signal and ΔIM3 is a power difference between mixing product and one test tone signal. The CW signal is not optimal test signal for a wide band receiver and a modulated test signal is preferred.

We performed IP3 testing with a digitally modulated 100MHz test signal. The modulated test signal can be considered to be the same than two CW test signals in the two-tone test. The power of modulated test signal may be considered to be shared to both CW signals and (1) is modified for modulated signal case, so that $P_{\text{tone}} = P_{\text{signal\_BW}} - 3\text{dB}$.

We measured the linearity of the proof of concept 5G mmW receiver with a 100 MHz wide 16-QAM modulated test signal with a roll-off factor α=0.35. The test signal was transmitted OTA to the antenna array of the 5G mmW receiver at 26.5 GHz frequency [1]. The receiver signal paths of 5G mmW array receiver were phased so that the main lobe of the antenna array pointed towards the test antenna. The phasing of the receiver paths was done with digitally controlled phase shifters and each receiver path had own phase shifter. A spectrum at the output of the receiver was measured and one of the measurement result is shown in Fig. 7. This measurement was done with a high input power level in order to show clearly the RX ACP behavior of the received signal. The channel and ACP powers were measured by integrating the signal over the modulation bandwidth and avoiding the roll-off region of the signal. Similar ACP measurement method is used with WCDMA and LTE transmitter already. The measured spectrum shows clearly that the receiver has limited linearity since the received signal has significant spectral regrowth to the adjacent channel lower operating channel f1 as illustrated in Fig. 6. The ACP value of the received signal in Fig 7. corresponds the IM3 level in the two-tone test in Fig. 6.

The level of the test signal was varied and a summary figure of the linearity measurement results is shown in Fig. 8. It can be seen that the output spectrum of the receiver is not completely symmetrical and the average of the lower and the higher side ACP results gave the most stable result. The measured IIP3 of the array receiver at 26.5 GHz operational frequency is −5.4 dBm, which can be seen from Fig. 8. The linearity of the first LNA dominates the linearity of the array receiver and the specification of the IIP3 of used LNA component is –4.0 dBm. The third-order non-linearity expects that the slope of the 3rd order intermodulation (IM) product is 3:1. Our measurement results show that the slope of the IM3 is 2.4, which is a good match with the theoretical value.

The linearity of the 5G mmW proof-of-concept receiver need to be validated at frequencies outside of mmW frequencies and future work includes the linearity measurements of the array receiver with Wi-Fi and LTE LAA test signals.

Conclusions

First version of the 3GPP standard for 5G NR mmW radios was released at end of 2017. The requirement of TX ACLR for 5G NR mmW transmission is specified with OTA measurement, only. The OTA ACLR, as a TRP, does not take into account the direction of the interference. We have introduced directive ACP in earlier papers. We emphasis that directive ACP would enable enhancement in environment where there are restricted geographical interference limitations like radars or zone edges.

Multi-radio interoperability requirements between 5G NR mmW radio and other radio systems like Wi-Fi and LTE is standardized. We indicated that current LTE LAA standard do not cover 5G mmW interoperability.

We evaluated the linearity of proof-of-concept 5G mmW receiver with OTA measurement with a modulated 100 MHz wide mmW test signal. The used linearity measurement method of the receiver was similar to the ACP testing of LTE transmitter. The measured linearity of the array receiver to the main beam direction follows a third order linearity assumption as expected.

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