Marko Leinonen

OVER-THE-AIR MEASUREMENTS, TOLERANCES AND MULTIRADIO INTEROPERABILITY ON 5G MMW RADIO PLATFORM
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Abstract

In this dissertation, the author has studied how a proof-of-concept (PoC) prototype for 5G millimeter wave (mmW) radio can be built and its performance can be analyzed against tolerances and anticipated product requirements without the guidance of the 3rd Generation Partnership Project (3GPP) standard requirements. It was shown in the thesis, that the development of a system-level PoC radio unit resembles closely the development process of the industrial product. 5G mmW radio needs to be tested using over-the-air (OTA) measurements based on the 3GPP standard. However, the 3GPP requirements were not available at the time of the PoC development. Here new measurement methods were developed by the author to test the developed PoC mmW radio.

Among OTA test techniques, error vector magnitude (EVM) measurement opens a new possibility to perform mmW measurements during communication signaling. Additionally, the use of mmW frequencies enables new OTA testing to be performed in an RF laboratory or office environments due to the small signal wavelength. As an example, the noise figure (NF) measurement for a mmW phased array receiver was demonstrated based on OTA EVM measurements in this thesis without expensive noise source equipment. Gain control both in the transmitter and the receiver were adapted to scale the required measurement range down in different OTA scenarios. This enables 5G mmW link range and cell coverage estimations with beam steering without cumbersome long-range outdoor measurements.

The higher 5G mmW frequencies challenge the current manufacturing methods for telecommunication products since the wavelength of the signal is shorter, and the absolute manufacturing tolerances are larger at higher frequencies. The shape of the probability density function of the radio parameters is needed for quality level estimation purposes, and it was proven in the thesis that the antenna input matching follows a log-normal distribution on the dB scale.

The product and measurement system calibration will not correct repeatability and reproducibility errors in the measurements. It was found that a standard deviation of the repeatability of the 5G mmW signal power level with OTA measurement in an RF laboratory or office environment is comparable with inaccuracies of modern OTA chambers for 4G OTA measurements.

Keywords: 3GPP, antenna array, C_pk, co-existence, EVM, noise figure, OTA, position accuracy, probability density function, quality, RF measurement
Tässä opinnäytetyössä, kirjoittaja on tutkinut, kuinka voidaan rakentaa konseptitodistuslaite (PoC) 5G millimetriaaltoradiosta (mmWave-radiosta) ja analysoida sen suorituskyvyä oletetta-vissa olevien tuote- ja toleranssivaatimusten suhteen ilman käyttöä olevia 3rd Generation Partnership Project (3GPP) -standaardin säännöksiä. Työssä havaittiin, että järjestelmätason PoC radioyksikön kehittäminen noudattaa hyvin teollista tuotekehitysprosessia.

5G mmWave-radioiden testaus tehdään 3GPP-standardeihin perustuen ilmarajapinnan yli (OTA), joita ei ollut saatavilla PoC radiokehityksen aikana, joten kirjoittaja kehitti uusia mittausmenetelmiä 5G mmWave PoC radion testaamiseen.

OTA mittausmenetelmien joukossa virhevektorin suuruus (EVM) mittaus avaa uusia mahdollisuuksia mmWave radioiden testaamiseen, sillä testausta voidaan tehdä kommunikointisignaalin avulla ilman erityistä testitilaa. Lisäksi, mmWave taajuuksien käyttö mahdollistaa uusia OTA-mittauksia, joita voidaan suorittaa RF laboratorio- tai toimistoympäristöissä ilman erityistä 3GPP-standardeja.

OTA mittausmenetelmien on demonstroitu käytävän OTA EVM mittauksista ilman kallista kohdinäyttökaartia. Lähettimessä ja vastaanottimessä on käytetty vahvistustyökalut, jotta mittausvirtauksia on voitu lyhentää eri käyttötilanteissa. Tämä mahdollistaa 5G mmWave taajuuden linkkihyvyyden mitatamisen ja solun kattaman alueen arviointiin säännöllisesti ilman kallista kohdillaa.

Suuremmat 5G mmWave -taajuudet haastavat tietoliikennetuotteiden kykyiset valmistusmenetelmät, koska signaalien aallonpituuksia on lyhyempi ja absoluuttiset valmistustoleranssit ovat suuremmilla taajuuksilla. Radioparametrien todennäköisyysjakauman muotoja tarvitaan laatu- ja tuotteiden estämiin varten, ja tässä osoitettiin, että antennin sisääntulo impedanssin muotoja on log-normaalijakaumaa dB-asteikolla.

Tuotteiden ja mittalaitteistojen kalibronointi ei poista mittausmenetelmien toistettavuuden keskihajontayksiköitä. Työssä havaittiin, että 5G mmWave signaalilaitteen mittauksen toistettavuuden keskihajontayksiköitä olikin suurimmilla taajuuuksilla.

Asiassanan: 3GPP, antenniryhmä, Cpk, EVM, kohdistustarkkuus, kohnaluku, latex, OTA, RF-mittaus, todennäköisyysjakauma, yhteistoiminta
To my Family.
Preface

The research work for this thesis was conducted at the Centre for Wireless Communications - Radio Technology (CWC-RT) Unit, University of Oulu, Finland, from 2017 to 2020. I want to express my sincere gratitude to my principal supervisor Professor Aarno Pärssinen, for his support and guidance throughout my doctoral thesis work.

I highly appreciate the reviewers of this thesis, Dr. Sc. Timo Tarvainen and Adjunct Professor Sven Mattisson, from Lund University, who helped improve the quality of the thesis significantly. I would also like to thank Professor Ari Pouttu and Dr. Sc. Marko Tuhkala for acting as members of my follow-up group.

The work of this thesis was carried out in several projects: 5G Communication with a Heterogeneous, Agile Mobile network in the Pyeongchang Winter Olympic competition (5GChampion), 5G Test Network+ (5GTN+), the Business Finland funded 5G Finnish Open Research Collaboration Ecosystem (5G-FORCE), Business Finland funded 5G-VIIMA and the Academy of Finland 6Genesis Flagship projects.

I would like to thank all my colleagues at CWC and elsewhere. I would especially like to acknowledge the current and former members of CWC: Dr. Marko Sonkki, Dr. Olli Kursu, Dr. Giuseppe Destino, Mr. Nuutti Tervo, Mr. Markku Jokinen, Mr. Jani Saloranta, Mr. Juho Rivinoja, and Mr. Nédio Chrystian da Silva Neddef. Additionally, I would like to thank my colleagues at Nokia Oyj, who worked on the 5GChampion project: Mr. Aki Korvala, Mr. Harri Mustajärvi and Mr. Tommi Kallio.

I am also grateful to my parents for their support throughout my life. Finally, I would like to express my deepest gratitude to my wife, Miia, for her love, understanding, and support throughout the whole doctoral thesis process and to children Veera, Lotta, Aleksi, and Tuukka helping me to forget work-related matters.

Haukipudas, November 5, 2020

Marko Leinonen
List of abbreviations

\( \alpha \) pathloss coefficient
\( \varepsilon_r \) dielectric constant
\( \lambda \) wavelength of the operational frequency
\( \Theta \) -3 dB beam width
\( \mu \) mean value
\( \sigma \) standard deviation
\( \Delta f \) frequency offset
\( \Phi \) cumulative distribution of standard normal distribution

\( G \) gain in (dB)

2G second generation
3D three dimensional
3G third generation
3GPP 3rd Generation Partnership Project
4G fourth generation
5G fifth generation
6G sixth generation

ADC analog-to-digital converter
ACLR adjacent channel leakage ratio
ACP adjacent channel power
AGC automatic gain control
ANOVA analysis of variance
AMPS advanced mobile phone system
ARB arbitrary waveform generator
bn billion
BB baseband
BER bit error rate
BLER block error rate
BTS base station
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BW</td>
<td>bandwidth</td>
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<tr>
<td>Bw</td>
<td>beamwidth</td>
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<td>CAD</td>
<td>computer aided design</td>
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<td>CDMA</td>
<td>code division multiple access</td>
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<td>CE</td>
<td>concurrent engineering</td>
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<td>CISPR</td>
<td>Comité International Spécial des Perturbations Radioélectriques</td>
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<td>CNC</td>
<td>computer numerical control</td>
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<tr>
<td>$C_{pk}$</td>
<td>process capability index</td>
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<tr>
<td>C-plane</td>
<td>control plane, control signal plane</td>
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<td>CST</td>
<td>Computer Simulation Technology</td>
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<td>CW</td>
<td>continuous wave</td>
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<td>dB</td>
<td>decibel</td>
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<tr>
<td>dBi</td>
<td>decibel compared to isotropic i.e. omni-directional radiator</td>
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<td>dBm</td>
<td>decibel compared to mW</td>
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<tr>
<td>dBc</td>
<td>decibel compared to carrier</td>
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<td>DFM</td>
<td>design for manufacturability</td>
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<td>DL</td>
<td>downlink</td>
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<tr>
<td>DMAIC</td>
<td>design, measure, analyze, identify and control</td>
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<td>DOE</td>
<td>design of experiments</td>
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<td>DUT</td>
<td>device under test</td>
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<td>EIRP</td>
<td>effective isotropic radiated power</td>
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<td>EM</td>
<td>electromagnetic</td>
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<td>EMC</td>
<td>electromagnetic compatibility</td>
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<td>EMF</td>
<td>electromagnetic field</td>
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<td>EVM</td>
<td>error vector magnitude</td>
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<td>FDTD</td>
<td>finite-difference time-domain</td>
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<td>FEM</td>
<td>finite element method</td>
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<td>FNBW</td>
<td>first null beamwidth</td>
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<td>FR1</td>
<td>frequency range 1</td>
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<td>FR2</td>
<td>frequency range 2</td>
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<td>FSPL</td>
<td>free space path loss</td>
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<td>G</td>
<td>gain of RF circuit</td>
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<td>GaAs</td>
<td>gallium arsenide</td>
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<td>Gage R&amp;R</td>
<td>gage repeatability and reproducibility</td>
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<td>Gbps</td>
<td>giga bits per second</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>GSM</td>
<td>global system for mobile communications</td>
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<td>GUI</td>
<td>graphical user interface</td>
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<td>HPBW</td>
<td>half-power beamwidth</td>
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<td>HW</td>
<td>hardware</td>
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<td>HAL</td>
<td>hardware abstraction layer</td>
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<td>IC</td>
<td>integrated circuit</td>
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<td>IF</td>
<td>intermediate frequency</td>
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<td>IMD</td>
<td>intermodulation distortion</td>
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<td>IP3</td>
<td>third-order intercept point</td>
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<td>IIP3</td>
<td>input third-order intercept point</td>
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<td>LNA</td>
<td>lower noise amplifier</td>
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<tr>
<td>LOS</td>
<td>line of sight</td>
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<td>LSL</td>
<td>lower specification limit</td>
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<td>LTE</td>
<td>long term evolution</td>
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<td>LTE LAA</td>
<td>long term evolution licensed assisted access</td>
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<td>LUT</td>
<td>look-up table</td>
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<td>MC</td>
<td>Monte Carlo</td>
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<td>MCU</td>
<td>main control unit</td>
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<td>MCM</td>
<td>multi-chip module</td>
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<td>MEMS</td>
<td>microelectromechanical switch</td>
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<td>MFR</td>
<td>manufacturing failure rate</td>
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<td>MIMO</td>
<td>multiple input multiple output</td>
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<td>MMIC</td>
<td>monolithic microwave integrated circuit</td>
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<td>mmW</td>
<td>millimeter wave</td>
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<td>MSA</td>
<td>measurement system analysis</td>
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<td>N</td>
<td>number of samples</td>
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<td>NF</td>
<td>noise figure in dB</td>
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<td>NFC</td>
<td>near field communication</td>
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<td>NR</td>
<td>new radio</td>
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<tr>
<td>OTA</td>
<td>over-the-air</td>
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<tr>
<td>P</td>
<td>power</td>
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<tr>
<td>PA</td>
<td>power amplifier</td>
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<td>PCB</td>
<td>printed circuit board</td>
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<td>PCI</td>
<td>process capability index</td>
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<td>PD</td>
<td>product development</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>PDP</td>
<td>product development process</td>
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<td>PDF</td>
<td>probability density function</td>
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<td>PL</td>
<td>path loss</td>
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<tr>
<td>PoC</td>
<td>proof-of-concept</td>
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<td>QAM</td>
<td>quadrature amplitude modulation</td>
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<tr>
<td>R</td>
<td>measurement distance</td>
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<tr>
<td>R&amp;D</td>
<td>research and development</td>
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<td>RF</td>
<td>radio frequency</td>
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<td>RFIC</td>
<td>radio frequency integrated circuit</td>
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<tr>
<td>RMS</td>
<td>root mean square</td>
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<tr>
<td>RX</td>
<td>reception</td>
</tr>
<tr>
<td>SAR</td>
<td>specific absorption rate</td>
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<tr>
<td>SMD</td>
<td>surface mount device</td>
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<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
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<tr>
<td>SPC</td>
<td>statistical process control</td>
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<tr>
<td>SW</td>
<td>software</td>
</tr>
<tr>
<td>SWOT</td>
<td>strengths, weaknesses, opportunities, threats</td>
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<tr>
<td>$S_{11}$</td>
<td>input impedance matching</td>
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<td>TDD</td>
<td>time division duplex</td>
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<td>TX</td>
<td>transmission</td>
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<tr>
<td>UL</td>
<td>uplink</td>
</tr>
<tr>
<td>UE</td>
<td>user equipment, mobile device</td>
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<tr>
<td>U-plane</td>
<td>user plane, communication data plane</td>
</tr>
<tr>
<td>USL</td>
<td>upper specification limit</td>
</tr>
<tr>
<td>VNA</td>
<td>vector network analyzer</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>wireless fidelity, wireless local area network</td>
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<tr>
<td>WCDMA</td>
<td>wideband code division multiplexing access</td>
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</table>
List of original publications

This thesis is based on nine peer-reviewed original articles, which are referred to in the text by their Roman numerals (I–IX):


The author had the primary responsibility for writing Paper I. The author proposed a new receiver’s noise figure measurement method based on the discussions and initial system level calculations by prof. Pärssinen. Contributions of each author to the paper can be seen from section 1.4.

The author had the primary responsibility for writing Paper II. The author proposed a Gage R & R-method to apply to study inaccuracies of the 5G mmW OTA measurements. The detailed information on the contributions can be seen from section 1.4.

The author had the primary responsibility for writing Paper III. The author proposed the analyzed interference scenarios for the paper and performed interoperability analyses between radio systems. The contributions of each author to the paper is discussed in section 1.4.
The author contributed to Paper IV by specifying, setting up the measurement system, and performed linearity measurements of the 5G PoC receiver. All contributions of each author to the paper are clarified in section 1.4.

The author had the primary responsibility for writing Paper V. The author proposed the process capability index $C_{pk}$ to be used with the quality analysis of the antenna module. The author contributed to the paper in several ways, and this is discussed in section 1.4.

The author had the primary responsibility for writing the Paper VI. The author proposed the 5G mmW and LTE interoperability scenario, which was studied with the developed 5G mmW PoC radio. Contributions of each author are clarified in section 1.4.

The author had the primary responsibility for writing Paper VII. The author proposed the measurement arrangement for measuring the OTA EVM performance, and section 1.4 covers details of contributions from each author of the paper.

The author had the primary responsibility for writing Paper VIII. The author proposed the measurement arrangement on how to measure the OTA EVM performance with beam steering. All contributions of the authors to the paper are discussed in section 1.4.

The author had the primary responsibility for writing Paper IX. The author proposed the connector misalignment study with implemented antenna arrays. Details of the contributions of each author are shown in section 1.4.

In all the original papers, the co-authors also provided valuable comments and criticism, which the author gratefully accepted. During the doctoral thesis work, 2017 - 2020, the author has also contributed to several other publications related to 5G mmW radio and antenna implementations, radio system engineering, and mmW measurement research.
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1 Introduction

1.1 Background and motivation for the thesis

The mobile phone market is the largest market for radio transceivers. The global market for mobile phones sold 1,555.3 million units during 2018, and the high-end mobile phone market accounted for 408.3 million units [1]. These extremely large manufacturing quantities require high-quality device designs so that the products can be manufactured cost-efficiently with a high yield. The number of manufactured mobile devices has grown on a yearly basis, and the same trend continues when the first fifth generation (5G) capable mobile devices came onto the market in 2019. The worldwide market for base station (BTS) units is not available from public sources, but in China alone, 3.7 million long-term evolution (LTE) BTSs were deployed by 2018 [2]. The market value of the LTE BTS market is expected to grow from 25.9 billion (bn) USD in 2017 to 72.0 bn USD in 2023 [3]. The 5G BTS market is expected to reach 95.4 bn USD in 2025 from 4.3 bn USD in 2018 [4].

The identified quality problems in mobile devices will introduce huge costs for device manufacturers. Several quality problems have been reported publicly [5, 6, 7, 8, 9]. The costs associated with correcting the hardware quality problems are one part of the problem, but in the long-run the image damage due to poor quality, may be even higher. In many of the reported quality problem cases, the root causes of the problem could have been avoided with appropriate product design. The quality of the product needs to be designed into the product, and thus methods for determining the quality level accurately during the development of the product is essential.

The past and currently used telecommunication systems from the first-generation analog systems to the fourth generation (4G) systems have been mainly deployed with macro base stations (BTSs) with broad cell coverages and on a smaller-scale with micro base stations. As an example, the third-generation (3G) wide-area BTS may cover 30 km$^2$ while the small cell version covers 10,000 m$^2$, only [10]. The need for small-sized and small cell BTSs has grown in 4G or with LTE since the indoor coverage has become a more significant parameter in network planning because 80% of LTE services are indoors [11]. The same trend will continue with 5G, where the usage of higher millimeter-wave (mmW) frequencies will shorten the distance between BTSs. The distance between 5G mmW BTSs is expected to be 200 m [12], which naturally...
limits the 5G mmW networks to operate as a small cell network, which will lead to a significant increase in the number of BTSs in the future wireless networks. The most significant difference between 5G mmW networks compared to previous generation networks and the 5G network deployed at sub-6 GHz frequencies is that the 5G mmW networks relay on beamforming and beam steering to enhance the link range of the mmW system [13]. Beamforming has been implemented in 5G mmW radios by using antenna arrays at both the transmission (TX), and reception (RX) ends of the radio link. The 5G BTSs can have hundreds of antennas in an array starting from 128 up to 384 antennas, while the first wave user terminals (UEs) will use four to eight antenna element arrays [14].

The development of new telecommunication generations has increased the demand for the supported frequency bands in the mobile and base stations since new generation device need to support earlier generation frequency bands as legacy support. Additionally, these devices need to support other wireless technologies as well, such as Wi-Fi, near field communication (NFC), and Bluetooth. This kind of multi-radio and multi-frequency support within a single device creates radio interoperability challenges. The 5G standards have already standardized almost 30 frequency bands and more than 1000 frequency band combinations [15, 16]. Thus, mobile devices need to support radio frequencies from 13 MHz up to 40 GHz. At the same time, these radio systems at different radio frequencies should not interfere with each other during simultaneous operations. There is no standard available on how much different radio systems may interfere with each other. All current standards focus on their frequency band allocations only and rely on general regulatory out-of-band requirements. In many cases, this is not sufficient for reliable devices.

The 5G mmW frequencies have shorter signal wavelengths compared to current 4G LTE systems. Tighter mechanical and electrical tolerances will be required for antennas, printed circuit boards (PCBs), and RF components at mmW frequencies for the same manufacturing technologies. Small physical dimensions, multiple ports, and highly integrated antenna arrays in 5G devices challenge currently used conductive measurements. For these reasons, the performance of 5G mmW radios will be tested over-the-air (OTA). Compared to conductive testing, OTA testing introduces has more error sources such as antenna radiation performances, antenna placement inaccuracies, and radiated signal fluctuation during testing. Additionally, OTA testing is more prone to external interferences during measurements compared to conductive testing.
mmW standard is under development, and many RF OTA test methods and procedures were not specified at the time of writing the thesis.

The author feels that there is room to contribute to 5G mmW measurement techniques, improved quality level estimation, and multiradio interoperability with 5G mmW devices, which are in the main focus of the thesis. The research problems are described in the following section.

1.2 Objectives and scope

The main scope of the thesis was to study non-idealities and tradeoffs based on a system-level proof-of-concept (PoC) 5G backhaul radio unit operating close to mmW frequencies. The PoC radio unit was developed at the University of Oulu in the Agile Mobile network in the Pyeongchang Winter Olympic competition (5GChampion) project [17].

The 5GChampion project had a fixed date for final demonstration since the 5G mmW backhaul radio prototype was demonstrated and showcased in the Winter Olympics in Korea in February 2018. The thesis is mainly based on the antenna and the mmW radio designs of 5G mmW PoC radio developed during the project.

One of the aims of the thesis was to develop a new system-level PoC radio unit in a short time to be as close as possible to a final 5G product, the missing radio test specification, as part of the 5G new radio (NR) mmW standard, set the focus of the thesis. The first radios for mmW frequencies were developed more than 100 years ago [18] and since then mmW radios have been measured. We studied available radio testing methods for mmW radios from the literature and documents from measurement equipment manufacturer before 5G mmW PoC radio measurements [19, 20, 21, 22, 23]. Conductive measurements methods were studied in detail, since they have been used extensively for below 6 GHz telecommunication radio development. The weakness of conductive measurements in mmW array measurements is that each array port would need own test signal, connector, and test cable, and thus such mmW radio test methods are cumbersome to apply. It was decided during the measurements of the first PCB version that the PoC radio needed to be measured by OTA means to overcome the complex cabling and shortage of power dividers operating up to 30 GHz. 5G standard-based test methods were not available during the development, and thus some new radio measurement methods for 5G mmW radio had to be develop during the project, and this thesis reports them.
Other focus areas of the thesis were, how to develop a PoC radio and an antenna array, and how to measure the 5G mmW radio and the antenna modules. Additionally, manufacturing and quality aspects of the radio and antenna modules are included in the scope of the thesis. The 5G mmW interoperability with other deployed radios nearby was studied to guarantee the operation of the 5G mmW radio link in the presence of other radio systems.

Based on the previously mentioned focus areas following research questions were formulated.

Q1. How can early radio prototypes be built for new standards like 5G before they are publicly available and how can their performance be analyzed with tolerances against anticipated product requirements?

The 5G mmW PoC was a system-level PoC development as it involved multiple aspects very close to actual product development rather than standalone technology PoC development. Typically university PoC projects aim to demonstrate the capabilities and possibilities of one selected technology. The customer requirements typically change during the development of the product, and thus a system of requirements management was implemented. The primary customer for the PoC were the Korean authorities responsible for the arrangement of the Winter Olympic Games and significant customer requirement changes occurred during the PoC development.

Q2. Can other lower frequency radio systems simultaneously operate with 5G mmW radio in the same radio unit or nearby?

The 5G mmW system will be deployed in the same area with existing radio networks such as Global System for Mobile Communications (GSM), Wideband Code Division Multiplexing Access (WCDMA), LTE, and Wi-Fi. Each transmission of s radio system introduce interference to the 5G mmW radio if they are operating nearby or within the same unit. Two inference mechanisms by which the lower frequency radio may interfere with the 5G mmW radio were studied in the thesis. In those cases, the harmonics of the lower frequency TX overlap with the mmW reception channel, or the fundamental lower frequency TX blocks the mmW reception.
Q3. Can 5G NR OTA measurements be performed in a RF laboratory or office environment without radio reflection attenuated electromagnetic compatibility (EMC) or antenna chamber? If, so, how accurate are the OTA results?

The radio performance of currently used cellular radio systems is measured with conductive measurements. However, the radio performance of 5G mmW radio will be measured in an OTA manner [24]. OTA measurements of current radio systems are performed in high-cost EMC or antenna laboratories due to the relatively large wavelengths and external radio interference mitigation. 5G mmW radio will have a significantly shorter wavelength than current LTE systems, and this may open the possibility to perform some OTA measurements without a costly EMC or antenna chamber in an RF laboratory or an office environment, where office furniture is arranged so it is away from the OTA measurement location.

Q4. Can the 5G mmW radio link range be estimated based on EMC chamber measurements?

The link ranges and coverages of current cellular systems are tested by conducting drive tests in real networks. However, outdoor measurements are prone to external radio interference, and the repeatability of the tests is poor. Current cellular networks cannot be tested in EMC-chambers in far-field conditions due to the used frequencies and device sizes. The 5G mmW system will operate above 24 GHz frequencies with wavelengths shorter than 12.5 mm. Thus, an EMC chamber with a 3-meter OTA test range equals at least 240 wavelengths at 24 GHz and the same test range at 1 GHz frequency (a low band LTE network) with a 30 cm wavelength would correspond to a 72 meter system.

Q5. How can the noise figure of a 5G mmW array receiver be measured in OTA tests?

A first method to measure noise figure (NF) is based on conductive measurement, where a narrowband noise level increase of the signal is analyzed when conveyed through the RX. An second method is to use a wideband noise source and measure the wideband noise level increase at the RX output. These methods are not easy to implement at a mmW frequency array receiver when multiple RX inputs should be fed at the same time with a wide RX bandwidth. Both currently used NF measurement methods have limitations concerning the dynamic range. The wide channel bandwidth
increases the thermal noise level significantly, and the available wideband noise sources at the mmW frequencies produce only a few decibels (dB) of white noise over the thermal noise level, e.g., 8 dB 26 GHz [25], 12.5 dB 50 GHz [22].

Q6. How can EVM measurements be utilized most effectively for wireless backhaul radio development?

The system error vector magnitude is a parameter that is not standardized in any cellular standards, but it is a system-level parameter. The system EVM is a combination of TX and RX EVMs, and thus, it cannot be tested easily with currently available lower frequency BTSs and UEs. The system EVM can be tested and be demonstrated easily with a wireless backhaul system where both ends of the system are similar. The system EVM measurement can be done with a 5G NR signal during the operation of the radio units or in the measurement mode of the radio units.

Q7. Can 5G mmW antenna array modules be manufactured at a mass production quality? How should the quality level of the antenna array module be estimated?

New 5G mmW radios will be deployed on a large scale in both base stations and mobile devices, and the quality level of mmW components need to be mass production capable. Currently used cellular antenna modules have fewer than five electrical contacts in UEs and ten in BTSs. The number of antenna contacts will exponentially grow in 5G mmW radios, where hundreds of antennas will be used in BTSs [14]. Each connection will increase the probability of manufacturing failure or the manufacturing failure rate (MFR).

Q8. Which probability density functions do different radio parameters follow? What are the tolerances for antenna modules for mass production, and are they derived?

The MFR depends on the probability density function (PDF) of the analyzed parameter and manufacturing acceptance limits. The manufacturing quality level or failure rate can be estimated with a statistical analysis where the tails of the PDF of the parameter are compared with the specification limits. For this reason, the PDF of the statistical population of the parameter needed to be derived. Additionally, the
specification limits need to be set so that components works as expected, and they can be manufactured at high production volumes.

The 5GChampion project was a system-level PoC project, which demonstrated that 5G mmW radio could be designed and manufactured to fulfill a data rate requirement of several gigabits per second (Gbps). However, one target was to provide insights into whether the 5G mmW radio and antenna designs were capable of volume production. Table 1 shows the relationship between the research questions and the original papers investigating them.

### 1.3 Research methods and materials

Comprehensive overviews of the available research and problem-solving methods are presented in [26, 27], respectively. The research for the thesis started by defining appropriate research questions. After the research question definitions, the work continued systematically towards solving the questions.

This research used analytical research and problem-solving methods such as statistical analyses of quantitative data, numerical simulations, as well as design of experiments (DOE) and Six Sigma -methods [28]. The quantitative data for the statistical analyses were acquired from RF measurements and based on numerical simulation results.

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Table 1. Relationship between the research questions and the results of original papers.
The 5G mmW radio units developed and manufactured during the 5GChampion project [17] were designed with state of the art mmW frequency components, which were available as off-the-shelf components at the time. The number of the available mmW components increased significantly during the duration of the project and doctoral thesis work since the first wave of 5G base stations [29] and mobile devices [30] were introduced to the public market in early 2019. The PCBs used in the 5G mmW backhaul radio units were manufactured at a tier-1 PCB factory. Surface mount device (SMD) soldering and wire bonding of the mmW die components were done by a professional company. The main mechanical body of the radio unit was manufactured by a company focusing on computer numerical control (CNC)-milling of metal parts. The final assembly of the radio unit was done on the premises of the University of Oulu.

The measured and analyzed 5G mmW antenna array module prototypes [31] were used with 5G mmW backhaul radio units, which have been developed in the 5GChampion project. The same PCB vendor was used to manufacture the PCBs for the antenna modules and the radio unit. Antenna connectors were mounted on the PCB by a company specializing in SMD assemblies.

The 5G mmW radio card and antenna array designs were done using computer aided design (CAD) tools. A 2.5D electromagnetic (EM) simulator was used to perform EM-simulations for the RF design. The 3D EM-simulations for the antenna design were performed using the electromagnetic software Microwave Studio by Computer Simulation Technology (CST). The EM-simulation results were analyzed in the original publications and the thesis. Both the 5G radio card and the antenna array supported the 5G NR standard time division duplex (TDD) band n257 covering frequencies 26.50 – 29.50 GHz.

The manufactured 5G mmW radio cards and antenna arrays were measured using conductive and OTA measurement methods with 5G NR test signals. The measurement results were analyzed for the original publications and the thesis. Additionally, continuous wave (CW) measurements were performed with a vector network analyzer (VNA) to measure the S-parameters of the mmW radio card and antenna module. The OTA measurements were performed in an EMC chamber, in a typical RF laboratory environment and outdoors.

DOE methods were used to optimize the number of needed simulations performed using the EM-simulators since the EM-simulations were highly time and processing power consuming. Statistical methods were used to calculate statistical inference in the data, and histograms were used to analyze and present datasets graphically. Statistical
analyses were performed in the Matlab and Minitab statistical software programs. The gage repeatability and reproducibility (Gage R&R) -method was used to analyze the accuracy and repeatability of the measurement results [28].

Numerical simulations and analyses were performed in Matlab to analyze expected quality levels of the antenna modules based on the measurement results from the antenna modules. Thus, the sample parameters were used to estimate the statistical parameters of the statistical population.

1.4 Contributions in original publications

The author had the primary responsibility for writing Paper I. The author made the radio link budget calculations with G. Destino. The author proposed a new noise figure measurement method based on the discussions and initial system level calculations by prof. Pärssinen. The author performed the error vector magnitude (EVM) and comparison noise figure measurements for the NF analysis. The author analyzed the coherence gain and EVM results for the paper, and he performed the coherence gain measurements. G. Destino contributed to the link budget calculations and the system level analysis covering the beam generation part. O. Kursu had the primary responsibility for the radio implementation, and radio frequency (RF) system design and M. Sonkki designed and measured the antenna array for the proof-of-concept (PoC) radio unit. Prof. Pärssinen guided the work, and contributed significantly to the overall system design.

The author had the primary responsibility for writing Paper II. The author proposed a Gage R & R -method to apply to study inaccuracies of the 5G mmW OTA measurements, and the Gage R & R -method was applied to the received signal level measurement with a developed antenna array. The author carried out statistical analyses and drew conclusions based on the measurement results, which were specified by the author. Additionally, the author specified and analyzed the used OTA measurement setup. N. Neddef and J. Rivinoja performed actual RF measurements, while M. Sonkki provided the antenna array for the measurement. Prof. Pärssinen guided the work.

The author had the primary responsibility for writing Paper III. The author proposed the analyzed interference scenarios for the paper and performed interoperability analyses of LTE and Wireless Fidelity (Wi-Fi) systems. The author proposed a 5G mmW receiver linearity measurement based on a 5G mmW modulated signal and carried out the linearity analyses. N. Tervo performed non-linearity analyses of the 5G mmW
transmitter, and he performed the linearization simulations. O. Kursu contributed to the writing of the paper. Prof. Pärssinen guided the work.

The author contributed to Paper IV by specifying and setting up a measurement system, which was used to perform the linearity measurements of the 5G PoC receiver. Additionally, the author contributed with O. Kursu and N. Tervo to the coherence gain measurements with varying signal bandwidths for the paper. The author contributed measurements of the linearity of the attenuation and EVM performance curves of the receiver with O. Kursu and N. Tervo. The author participated in the writing of the paper with O. Kursu, who had primary responsibility for the paper. O. Kursu designed, simulated, and had the primary responsibility for implementing the PoC radio. G. Destino carried out a link analysis for the modulations. Prof Pärssinen, with the help of S. Tammelin, A. Korvala, and M. Pettissalo, supervised the work.

The author had the primary responsibility for writing Paper V. The author proposed the process capability index $C_{pk}$ to be used with quality analysis of the antenna module. The author provided a system model of how and why antenna variation should be taken into account during the development of the radio unit in respect to the specification requirements. The author made a mathematical, analytical model of how the resonance frequency variation of the antenna resonance can be mapped to the variation of the antenna impedance matching. He performed Monte-Carlo simulations to verify the model with antenna matching measurement results, which he measured. He performed statistical analyses of the simulated and measured results. M. Sonkki designed and provided the antenna arrays for the measurements. N. Tervo provided help on the statistical analyses, and Prof. Pärssinen guided the work.

The author had the primary responsibility for writing the Paper VI. The author proposed the 5G mmW and LTE interoperability scenario, which could be studied with the developed 5G mmW PoC radio. The author performed the antenna isolation measurements with M. Sonkki, and the author performed conductive measurements with O. Kursu. The author determined the physical sources of the measured isolation resonances and performed co-channel and blocking analyses based on the the Wi-Fi power amplifier measurements by J. Rivinoja. Prof. Pärssinen guided the work.

The author had the primary responsibility for writing Paper VII. The author proposed the measurement arrangement for measuring the OTA EVM performance. He made noise figure calculations for the second version of the implemented PoC radio with 16 signal paths. M. Jokinen carried out the EVM measurements in the OTA laboratory, and the out-door OTA measurements were carried out by the author, M. Jokinen, O. Kursu,
and N. Tervo. The author analyzed the EVM measurement results with estimations of the expected link range with different modulations. Prof. Pärssinen guided and supervised the work.

The author had the primary responsibility for writing Paper VIII. The author proposed the measurement arrangement on how to measure the OTA EVM performance with beam steering, and he carried out a statistical Monte-Carlo analysis for the noise figure RF system calculations. The author proposed the method for measuring the filtering responses of the receiver array, and M. Jokinen performed the OTA measurements. O. Kursu carried out the implementation of the PoC radio card. The author and prof. Pärssinen contributed to the detailed technical analysis of the radio solution. The author provided a theoretical analysis of the system EVM measurements and how they correlated with the specifications. Additionally, the author analyzed the expected link and beam coverages based on the OTA measurements, which were performed in the EMC chamber by M. Jokinen. The author analyzed the EVM OTA measurement results with M. Jokinen. The author proposed the concept of beam breathing, which was proven with measurement results. N. Tervo and O. Kursu provided valuable information on how to conduct the measurements and analyses. Prof. Pärssinen guided and supervised the work.

The author had the primary responsibility for writing Paper IX. The author proposed the connector misalignment study with antenna arrays. The author developed the concept of the mapping of a probability density function (PDF) of the input impedance to the PDF of the mismatch loss. The author derived a method of how the PDFs of the input impedance and mismatch loss of the antenna array could be derived from the antenna element PDFs. The author made measurements on the connector positioning the antenna array and the manufacturing accuracy of the metal back of the array. He performed all the statistical analyses and a multi-dimensional analysis for the measurement and simulation results. He measured the conducted antenna element results, and he guided and helped with the OTA measurements. M. Sonkki provided the antenna prototypes, and he performed the EM-simulations for the antenna element and the array. The author showed how the analysis could be extended to mobile devices, and he performed a case-study analysis. N. Tervo provided valuable comments on what and how to improve the manuscript. Prof. Pärssinen supervised the work.
1.5 Outline of the thesis

The dissertation is organized as follows: The first chapter outlines the research problem and objectives and provides some background information regarding the topic. The prototype development cycle and a relation to the proof-of-concept development process is discussed in chapter 2. The OTA measurement techniques are covered in chapter 3, and the manufacturing and the quality-related topics, as well as statistical properties of the RF parameters, are studied in chapter 4. Radio interoperability topics are reported in chapter 5, and a summary of the original papers are presented in chapter 6. Chapter 7 discusses the main findings and limitations of the thesis, future work, and potential applications of the results. Finally, chapter 8 presents the conclusion of the thesis.
2 Prototype development cycle

This thesis studies some key aspects of the system-level PoC from the development process and technical perspectives. This chapter gives an overview of the developed 5G mmW PoC radio and maps the system level PoC development process using a product development process widely used in the industry. The developed 5G mmW PoC radio platform was used as a test platform during the thesis, where the main findings of the thesis have been implemented and verified.

2.1 5G mmW network deployment and wireless backhaul

There are two primary use cases for mmW radios in the 5G network. 5G mmW radio communication can be used between user equipment (UE) and a base station (BTS), which in most of the literature is discussed as a 5G mmW network. Additionally, mmW radios can be used in communications between fixed radio network elements. In this case, mmW radios operate as a backhaul link, which can be further divided into two categories: A) a fronthaul link, which communicate between a BTS and digital baseband (BB) unit or between a small cell BTS and a macro BTS, and B) a midhaul link, which communicates between a remote radio head and a macrosite [32, 33]. Alternatively, a midhaul link can be used to aggregate traffic from multiple small cell BTSs, which are located at the macro base station [33]. 5G networks will utilize wireless backhauling much more than previous telecommunication systems since 5G network deployment will use significantly more small cell base stations than previous telecommunication generations. The 5G small cell BTS installation cost will be a significant challenge in 5G mmW network deployment to achieve the 5G goal of providing 1,000 times more capacity than the previous LTE network. This goal can be achieved only with 5G mmW small cells.

Commercial 5G mmW networks are deployed based on 3rd generation partnership project (3GPP) standards, and the 5G signaling is used between 5G mmW UE and 5G BTSs, as shown in Fig. 1. These networks operate from 24.25 GHz to 29.5 GHz and from 37.0 to 43.5 GHz frequency bands [16]. The first 5G networks have been deployed at sub-6 GHz frequencies as a dual connectivity network or non-standalone 5G network based on Release 15. The 5G dual-connectivity network uses 5G for the data connection (U-plane in Fig. 1) and LTE for control signaling (C-plane in Fig. 1) [34].
The first 5G mmW networks were opened in April 2019 [29] with dual-connectivity. True 5G networks, where user and control data are delivered over 5G, are expected to be launched in 2020 at sub-6GHz [35]. It may be possible, in the future, to deploy 5G mmW networks without dual-connectivity as a stand-alone network, if the 5G mmW coverage is sufficient to support UE mobility [35].

The mmW communication is shown with dashed arrows, and the LTE communication is shown with a solid arrow in Fig. 1. In the figure UE1 supports 5G mmW network only in 5G-mode while UE2 supports 5G mmW operation in dual-connectivity mode. The 5G mmW small cell is shown in yellow, and UE2 is supported by the directive coverage of the small cell mmW BTS. The midhaul link from the small cell BTS to macro BTS is shown with a blue dashed arrow. The mmW midhaul link (some references call this as a backhaul link) may use 5G communication signaling, or it may support proprietary signaling since it is an internal interface of the network. If the mmW midhaul link uses 5G signaling then the small cell BTS may support self or integrated backhauling [36]. The standardization has been concentrate on mobile and base station equipment separately in 3GPP release 15. An integrated access and backhaul equipment is targeted for inclusion in Rel. 16 from June 2020 onwards [37]. The 5G backhaul BTS may
operate as a base station or a mobile station mode in backhauling operation, additionally, the BTS acts like a typical BTS in communication mode. The BTS control software (SW) can select the operation mode of the wireless backhaul BTS based on the required operation mode.

A wireless backhaul system provides flexible installation options for 5G operators. The deployment of microwave or mmW backhaul radio requires a one-time capital cost and additional expenses such as rent, utility costs, and maintenance fees. Thus, a radio link based backhaul can be deployed at a much lower cost, and the deployment time is much shorter compared to a fiber-based connection [38]. The performance of microwave RF backhaul solutions varies significantly due to varying outdoor propagation environments and weather conditions. Very high order digital modulation schemes, e.g., 4096 quadrature amplitude modulation (QAM) and ultrahigh spectral-efficiency technique, e.g., line of sight (LOS) multiple input multiple output (MIMO), to support data rates up to 10 Gpbs, can be used with proprietary solutions [38].

The developed 5G mmW system-level PoC was planned to operate with a 5G NR signal, and the primary use case was to provide a high data rate link for mmW backhauling purpose. Additionally, it could be used as a limited coverage small cell BTS, but there was no support for self-backhauling functionality in the device.

2.2 Product development process

The development of system-level PoC, e.g. 5G mmW radio unit, includes integrating several new technologies into the same mechanics, including electrical parts, hardware components, the main control unit (MCU), and the controlling software. Thus, the system-level PoC development steps have significant similarities to the product development process (PDP) used in the industry, such as for base and mobile stations.

The research & development (R&D) function of an organization has the main responsibility for product development (PD), which includes preliminary assessment, system-level concept development, product development, and testing phases of the product [39, 40, 41]. A linear PDP process or a waterfall PD process is shown in Fig. 2, where all phases linearly follow each other in a timely manner. The PDP process starts from the planning phase, where product requirements are set based on market analyses and regulatory requirements. The concept design includes feasibility studies of potential components and electrical, thermal, and mechanical simulation studies to comply with user interface and industrial design requirements.
Fig. 2. General linear product development process.

Fig. 3. Nokia product development process in 2007.

System-level design defines the requirements for each principal and functional block and the interconnections between them. The block-level and circuit design phases are the primary phases where new product development happens. This phase is followed by testing and integration, where different parts, and sub-assemblies from hardware and software development are integrated. The final step is to release the product for production after successful product integration and verification tests. A tolerance analysis to determine the functional and tolerance limits is needed before the integration and testing steps to maximize the success of the prototype production [39].

An example case of the general PDP process is shown in Fig. 3, which is a simplified version of the process used by Nokia Mobile Phones in 2007, when it was the leading manufacturer of mobile phones [41]. At the end of each process step, a demanding tollgate review was held to guarantee the product design’s quality level. The reviews ensured that the product design was mature, and that the production yield estimation for the mass production was at an acceptable level. After-sales, maintenance, and production support functions were tightly integrated into the PDP process. Nokia especially mastered customer-care in the PDP to guarantee excellent quality service for customers when the warranty period was over, or the phone model was no longer in production [42].

The previously presented PDP process charts are simplified versions of real-life processes, which are multi-dimensional, complex, concurrent engineering processes. Concurrent engineering (CE) was introduced in the 1990s [43, 44] to model complex engineering processes more accurately.

Large, international product design and manufacturing companies have successfully implemented the CE process for over 30 years to enhance product development for
high volume products. One of the success factor in the process deployment has been that design teams have operated seamlessly together between each other and in close cooperation with suppliers. However, the benefits of the implementation of the CE process for small and midsize enterprises are not clear. The university environment can be included in the small enterprise category, since the available R&D and support function resources are limited. Applying the CE process requires additional work from R&D teams, support organizations, and management compared to the traditional linear PD process. The availability of data has changed dramatically in 30 years, and now the analysis and the usage of big data is a new and essential topic to be included in the CE process [45] and modified versions of the CE process have been presented in [46, 47].

In conclusion, the CE process has been one of the success factors to guarantee high quality and volume electronic product manufacturing over the last 30 years. CE process deployment requires excellent communication between all parties involved in product development and manufacturing, including support functions. The suppliers of components and sub-assemblies play an equally important role in enabling continuous and high-quality products since the quality level needs to be designed into the product. There is a common understanding that 80% of costs are fixed once the product design and manufacturing technologies are selected [48, 39]. The CE process is mainly deployed by international and well-established companies, while smaller companies and universities are use a traditional linear PDP process due to limited resources.

2.3 Design for manufacturability

The R&D team, which is in a university environment, a team of researchers led by an experienced researcher, is responsible for developing a product manufactured with available components at a selected manufacturing facility, fulfilling agreed and required functions within the agreed budget. An important part of R&D work is to optimize block- and circuit-level designs so that the product can be manufactured with acceptable MFR, and to ensure that the products are durable in normal usage. The design optimization towards production requirements is called design for manufacturability (DFM). DFM work is included in all the PDP process steps shown in Fig. 2. The general manufacturing requirements for the product size, weight, manufacturing time, and requirements for test time should be agreed in the planning and concept phase of the PDP. The definition and development of test methods used during R&D and manufacturing phases require significant work already during the system design phase.
The production test cases, production jigs, and the testing interfaces are jointly developed between R&D and production testing teams during the circuit development phase. The integration and testing phase utilizes the testing functions, and automated testing is performed as widely as possible to increase the testing coverage. Production testing is performed on the production line either as an on-line testing or off-line testing. Off-line testing can be an extended version of on-line testing, which is a highly optimized test routine to maximize the throughput of the production line.

The loopbacks between design iteration and production phases, and between integration & testing and the design iteration phase and the production phases are omitted in the product development process shown in Fig. 2. These internal loops between different phases of PDP are illustrated with a spiral PDP figure in Fig. 4 which has been inspired by a four-quadrant of SWOT diagram (strengths, weaknesses, opportunities, threats) [49]. The SWOT table has been significantly modified, and thus the Fig. 4 does not follow the original analysis principle. The four-quadrants can be seen as a spiral representation of the life-cycle of the product development. The upper left quadrant represents the first phases of the design where the definition and actual circuit or antenna design have been done. The design has been done with typical parameter values to match the product and design requirements. An alternative presentation of a spiral PDP has been presented in [40], highlighting different process phases.

The spiral PDP cycle starts from the circuit and system design phase in Fig. 4. The circuit and block-level designs are done in this phase to fulfill the required performance based on a system analyses. In the prototype rounds, special attention is needed for statistical tolerance analysis for mechanical and electrical circuits. The tolerance analysis and design target or mean value optimization is done with simulation software at the block-level. The mean value optimization and centering can be done using the DOE or Taguchi -methods [50] to optimize the production yield and production testing pass rate.

Manufacturing processes always involve some variability that needs to be included in the circuit design. The variability can be included in the design by using realistic circuit models supplied from the component manufacturer or by including variability in the component tolerances in the simulations. Statistical Monte-Carlo (MC) simulations need to be performed with parameter variations for optimized designs. The variability makes the optimization of the design more complicated due to the increased parameter optimization space. It is essential to understand the statistical properties and distributions of the design parameters to model the variability of the circuits and components correctly to estimate the yield of the production. The design can be delivered to the manufacturing
units after the design parameter optimization, and the simulated yield needs to be compared with the real manufacturing data after each prototype production round.

A detailed analysis of the design for manufacturability focuses on individual parts and components to optimize the production by reducing or eliminating expensive, complicated, or unnecessary features. The analysis of the design for assembly focuses on the reduction and standardization of parts, sub-assemblies, and assemblies to speed up manufacturing. The failure mode analysis identifies potential failure modes and failure rates of the circuitry, systems, product, or components prior to actual production. The design-based errors of the circuitry, component, system, or product can be studied using a design failure mode analysis. In a study [51], the applicability of these methods was studied for a total of 32 manufacturing and design process phases. It was noticed that failure mode analysis was the most versatile quality tool when it is focused on manufacturing and design analysis separately.

The number of manufactured prototypes is related to the available budget and availability of the components. Typically the number of the prototypes is maximized to guarantee enough working devices to be tested in the design validation phase. The production of prototypes needs to be adjusted during the manufacturing to optimize the yield of the production due to manufacturing process parameter fluctuation.
most commonly used method for process control is to use statistical process control (SPC) methods. In these, some randomly sampled products are measured, and based on these statistical process control indices (PCI) are calculated. If statistically significant parameter changes are noticed, then the control parameters of the production line are adjusted to improve the quality of the production. For selected product categories such as measurement cables, laboratory equipment, and measurement equipment, all products are 100% tested during the production to provide measurement data with the product. For consumer market products, 100% test coverage is not meaningful due to reduced production capacity. Thus, the on-line testing time is one of the parameters, which needs to be optimized in high volume production.

All telecommunication products need to comply with regulatory requirements, e.g., FCC requirements in the US, especially part 15 [52] and the EC requirement in Europe [53]. Selected main RF parameters are tested in mobile and base station production to ensure compatibility with the regulatory requirements. There are different methods to select the testing limits for production and product validation. One approach is to use the same, fixed specification limits in the production acceptance limits and in the product validation measurements. An alternative method is to use different specification limits in different phases of the PDP. This approach was proposed in [39], where there are different tolerance limits for functionality, performance, and regulatory approvals. This specification optimization for each purpose may increase the overall manufacturing throughput. Different specifications in separate process steps will hinder fluent communication between various parties involved in the manufacturing.

The design validation measures the design and manufactured circuits of the product. The number of tested individual parameters is highest with first prototypes, but typically the number of samples is limited due to high manufacturing costs. In the following prototype rounds, the number of measured parameters is reduced based on the criticality of the parameter, but the number of units is increased accordingly. Thus, the total testing time of the prototype round remains substantially constant. The confidence intervals of the most critical RF parameters are narrowed in each prototype round. The measurement methods and systems used will introduce errors to the measurement results, which need to be minimized. The deviations between measurement and simulation results are used to correct the simulation models and to center the design parameters to optimize the yield of the manufacturing process.

The number of parameters that can be studied in the upper quadrants is much higher than in the lower quadrants in Fig. 4. Parameters and their settings are easy to
modify in design software, and the number of simulation points exceeds the number of implemented physical prototypes drastically. However, simulated and measured values should match, and simulation models need to be adjusted accordingly.

A waterfall model of the system level requirement for the development process in an aerospace and electrical equipment manufacturing process is described in [54]. In this PDP model, system engineering steps and production line functions with involved on-line testing were mapped onto the same timeline. In the first phase, the production site was selected from a list of available original design manufacturers. Mechanical, electrical, and thermal simulations were performed based on system requirements, and PCB design has been performed based on these simulations. The design of printed circuit board assemblies is done with experts from production and R&D persons to optimize production time, yield, and testing. If the product is optimized for the known manufacturing process, then the optimization is important prior to the first pilot production since, in the optimal case, no further pilot production round is needed prior to the mass production [54].

All previously mentioned process steps were faced during the 5G mmW PoC radio development. The manufacturing sites were mainly selected from local factories enabling fluent communication. Several joint meetings were held between the university researchers and factory teams to solve manufacturability problems in different technology areas. The circuit-level designs, e.g., radio card and antenna PCB designs, were modified based on manufacturability feedback from the factory teams in the design reviews.

Requirements management in spiral PDP methods is located at the center of the quadrants in Fig. 4. The requirements management involves all process steps from the definition of the product to the final manufacturing. The customer, external regulatory, standard requirements and internal quality targets provide boundaries for the design

![Fig. 5. Requirement cycle in PDP, reprinted by permission Paper V ©2018 IEEE.](image-url)
Table 2. Contributions of the original papers mapped to the proposed spiral PDP model.

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of the product or PoC demonstration. If there are changes in the requirements, they need to analyzed and taken into account in the next process step and prototype round. The customer, standard, and regulatory requirements are drive the design, and are used to set specification limits for validation measurements. The requirements cycle over different process steps is shown in Fig. 5. The high-level requirements for radio circuits can be done based on the regulatory and standard requirements if they are available. If not, then the best understanding of similar systems can be used as basis for the requirements. Based on the main requirements, the system-level design for the radio solution can be achieved. The systems-level design is divided into circuit and block-level design targets as well as design targets for interfaces in the R&D phase, as shown in Fig. 5. The production design documents, including the specification limits are delivered to the manufacturing. In author’s experience from industrial R&D projects it is common that the same specification limits are used in different process steps to ease the communication between R&D, manufacturing, and validation teams [55].

The original papers and their contributions have been mapped into the new spiral PDP shown in Fig. 4 and the summary is presented in Table 2.

2.4 Case study: Development of a 5G mmW PoC radio unit

The development of 5G mmW PoC radio unit during the 5GChampion project, including radio cards and antenna array modules is analyzed as a case study based on the linear and spiral product development cycles presented in Figs. 2 and 4, respectively. The definition of PoC is very wide, and thus a new classification for different kinds of PoCs is proposed in Fig. 6. The type 1 PoC is concentrates on basic technology, component, or sub-system technology development. The type 2 PoC integrates multiple type 1 PoCs and other components based on standard technologies into the system-level PoC, which may be a technology platform, or a final product such as PoC. Type 2 PoC covers
platform developments, which can be mass-produced, if needed. The developed 5G mmW backhaul radio unit in the 5GChampion project belonged to the type 2 category.

A snapshot of the project plan for the development of the 5GChampion radio unit is shown in Fig. 7. This snapshot of the project plan shows how radio and antenna modules were integrated into the radio platform. It can be seen from the plan, that multiple hardware (HW) components were developed in parallel, which were later integrated. The project plan shows that HW development was done in tight co-operation with manufacturing and sourcing teams to make sure all the components were in production on time. Formal reviews of the RF and antenna designs were held as in industrial counterparts, where schematics and board layouts were checked and approved. Tollgate reviews are not widely used in university projects. However, they are held regularly on the projects which are tightly bound to the manufacturing process, such as in radio frequency integrated circuit (RFIC) tape-outs or antenna releases for the production. The PDP process was strictly followed as if the PoC was an industrial technology platform development rather than a single research prototype. The PDP process was selected to guarantee the best achievable quality level from the design perspective, even though the RF and antenna designs were carried out at university. The development of the control SW modules is not shown in Fig. 7 for clarity, but they were developed in parallel according to the CE process definition.

Fig. 6. Proposed classification of different kind of PoC's unit.
The requirements management of the 5GChampion, related to the 5G mmW PoC radio unit, was done at the University of Oulu. There were significant open requirements until the second round of the mmW radio card manufacturing phase [VII]. For example, the maximum allowed transmission power, the operational frequency channel, and the link range of the demonstration at the Korean Olympic demonstration location were not fixed until a few months prior to the event due to other 5G demonstrations in the same venue. Some new requirement changes were not possible to include in the design due to late information and highlight the importance of the fixed requirements before the concept and feasibility study phases. Earlier, the main requirements are known better the customer requirements can be taken into account in the actual circuit and product designs.

The first prototypes of the radio card and the antenna module tried to include all known 5G mmW requirements before the actual specifications were available. A 5G mmW system-level analysis was performed in [56], which was a good starting point for the development. The leading design principle was to find and design as good as mmW frequency coverage as possible based on off-the-shelf components. The first incomplete 3GPP standard version for 5G NR mmW with three frequency bands was available only in December 2017, and all system-level work was finalized before that.

The antenna module development followed the PDP process as described in section 2.2, where the concept design for the antenna array was based on previous projects. The first design of the 5G antenna module was done based on 15 GHz mmW array, while the 5GChampion project targeted 28 GHz. The developed radio unit can be considered to be

Fig. 7. Snapshot of development plan of the 5GChampion PoC radio unit.
a complete radio platform development. It included the following main parts: a new 5G mmW radio card, two antenna module versions (linear slant +45° and -45°), a new analog baseband card, a new mechanical design, and a separate attachable MCU with a new control SW.

One target for the PoC development was to study if the used components and component technologies could be used in mass production of 5G mmW radio units. State-of-the-art components were selected for use in the mmW radio design, and multiple bare-die components were chosen to be used in the design. These components were die-bonded to the PCB by a company specialized in this. Several components were damaged in the production due to die cracks during the bonding process with the first RF card version [57]. Die bonding problems occurred with the second RF card production in almost all manufactured RF cards with multiple components [58]. Similarly, die bonded mmW components were found to be not suited for high volume manufacturing based on two RF card production round experiences, but they were the only ones available at the time of the mmW board design. Packaged mmW components supporting the SMD process need to be developed before the mass-production of 5G mmW products can be done in large volumes.

There were three different versions of the antenna modules developed for both polarizations. Two first antenna modules had the same PCB, and the -45° polarized version is shown in Fig. 8. Two antenna module versions had different back covers made from different materials and based on different designs. The first back cover version was done from brass, but it was found to be too thick to be used with a 5G radio unit. The second back cover version was made from aluminum, which was thinner than the brass version. The measured performance of the first and the second antenna modules was similar. The second back cover was fit with the second antenna PCB, which created the third version of the antenna module shown in Fig. 9. Pin guide holes for the antenna assembly production jigs were introduced to the second antenna PCBs as shown in Fig. 9. The holes were added to improve the location accuracy and ease the installation of the back cover. A coplanarity problem was noticed in the assembly of the antenna module, since bending of the back cover introduced a gap between the back cover and PCB. The effect of the gap on the impedance matching was studied in [IX].

The second PCB enhanced the operational band to cover frequencies from the 26.3 - 28.2 GHz to the 24.5 - 28.8 GHz. It was noticed that there were unwanted cavity resonances in the first antenna modules. The impedance matching of the power distribution of the antenna module was improved by adding a quarter wavelength via
Fig. 8. First version of the 5G mmW antenna array module, reprinted by permission [31] ©2018 IEEE.

Fig. 9. Second version of the 5G mmW antenna array module, Paper [IX].
a grounded stub in the feeding network. The quarter-wavelength stub stabilized and improved the impedance matching at the highest frequencies. The antenna patch was modified as well to improve the frequency coverage. The grounding of the antenna module from the first PCB to the second PCB was enhanced by adding solid grounding and added ground via patterns.

Thus, the antenna module development followed a traditional step-wise development process. Similarly, the antenna module development can be seen as an example of spiral development process as shown in Fig. [4], where design improvements were made based on experiences and measurement results of the previous prototype versions.

Software development to control the 5G mmW radio unit was based on software platform thinking where each functional block was developed as a stand-alone module. The implemented control SW architecture is shown in Fig. 10. The lowest level SW is marked in blue, which is the hardware related driver SW. The hardware abstraction layer (HAL) is the layer marked with orange, for which the hardware dependency of the higher SW levels is decoupled. The implemented control SW and associated graphical user interface (GUI) can control the TX and RX operations separately. A high-level
SW block, shown in green, can control the gains of the TX and RX signal paths, the operational frequency, the direction and shape the beams, and select signal paths of the array transceiver. The GUI has been programmed with Matlab GUI generator while the rest has been implemented using the C-language.

The SW development started with the first PCB version [IV], where the HW related driver development was done with 8 signal paths. The higher level SW development was done with the second PCB version [VIII], where 16 signal paths for TX and RX were implemented. The operation of the higher level SW required that the RF card was integrated into the final mechanics with the AUX board. A photograph of the developed radio 5G mmW unit is shown in Fig. 11.

The photograph of the 5GChampion demonstration booth at the PyeongChang 2018 Winter Olympics is shown in Fig. 12, where the developed unit was demonstrated.
Fig. 12. 5GChampion project booth at Pyeongchang 2018 Winter Olympics in Korea, photo by Marko Leinonen.
3 5G mmW OTA measurements

3.1 Overview of 5G mmW OTA testing

RF performance measurements for current LTE telecommunication radio transceivers have been done using conductive measurements in [15, 60]. The reason for using conductive measurements for performance testing is that they are repeatable and reliable. The RF measurements’ complexity increases when the number of antenna ports increases in the radio transceivers due to MIMO, diversity reception/transmission, and antenna array support. The number of needed measurement connections and cables increases, and at the same the probability of measurement errors and uncertainty of the measurement increases.

OTA measurements been taken in EMC and antenna chambers for mobile devices and BTSs from analog systems, e.g., advanced mobile phone system (AMPS) onwards for LTE standards. EMC-chambers are targeted at lower frequencies than antenna chambers. EMC-chambers are designed to be RF anechoic chambers that absorb and suppress unwanted radio waves. EMC-chambers attenuate signals from low frequencies to RF frequencies. The EMC chamber’s highest operating frequency is limited by the size and properties of the absorber pyramids in the chamber. Antenna chambers are designed to be used at higher RF frequencies, and smaller size absorber pyramids are used to suppress radio wave reflections at operational frequencies. If an EMC-chamber operates at the measured antenna’s operational frequency, then the EMC-chamber can be used as an antenna chamber.

The low-frequency absorption of an EMC-chamber is done with ferrite tiles behind absorber pyramids. The absorption effectiveness of the pyramidal absorber is related to the length of the pyramid, and for 30 dB absorption, the length needs to be approximately 0.8 λ or longer [61]. Thus, the selection of the size and material used in the pyramid absorbers determines the chamber’s operational cutoff frequency. There are pyramid absorbers commercially available, which are characterized up to 110 GHz [62].

OTA measurements have been mainly concentrated on radiated TX power levels of UEs in different operational modes and use cases [63]. Radio performance measurements such as the adjacent channel power (ACP), adjacent channel leakage ratio (ACLR), TX frequency error, TX signal modulation quality, or TX error vector magnitude have not been carried out as OTA measurements in the previous telecommunication generations.
Fig. 13. Overview block diagrams of OTA measurement arrangements.

They have been verified to comply with operator requirements. An overview of block diagrams showing OTA measurement setups is shown in Fig. 13. The device under test (DUT) may be located at each end of the OTA measurement link depending on the TX or RX measurement to be performed.

Outdoor OTA tests, which have been carried out for current telecommunication networks, have been mainly used to validate the coverage of BTSs. Drive testing has been used to test the cell coverage, but it suffers from weather conditions, data traffic of the cell, moving objects such as cars, and external interference. The repeatability of such outdoor measurements is weak, and the results are environment-dependent. OTA testing in EMC chambers with current LTE frequencies is for micro-scale testing compared to the macro-scale outdoor drive tests.

The same trend will continue with future sixth generation (6G) telecommunication systems when they are deployed for the 100 - 300 GHz frequency band. There is already a standard proposal in IEEE 802.15.3 for Wi-Fi-like operation for a frequency band from 252.72 GHz to 321.84 GHz [64]. For this 300 GHz system, 5G mmW OTA measurement facility will be a macro-scale measurement environment, since the wavelength at the 300 GHz is 1 mm.

Separate testing is done for current 3G and LTE mobile and base stations. The combined performance has not been typically OTA measured in an EMC environment due to operational frequencies requiring a large EMC chamber. These kinds of OTA measurements are challenging or impractical at most used telecommunication frequency bands with typical BTS radios and antennas. The 5G mmW system opens new possibilities for OTA testing in laboratories.

The 5G NR is a new modulation scheme that will require HW upgrades at BTS and UE units over the LTE system. The 5G NR standard includes all current LTE frequency bands below 6 GHz, called frequency range 1 (FR1) and new mmW frequency bands from 24 GHz up to 43 GHz called frequency range 2 (FR2) bands. The first 5G
networks will be deployed at new frequency bands, for example, at frequencies around 3.5 GHz, e.g., at bands n42 and n43 [16]. The maximum channel bandwidth below 6 GHz frequency bands is limited to 100 MHz, while wider channel bandwidths up to 400 MHz can be supported at mmW frequencies [16]. As mentioned previously, all RF performance and verification measurements at 5G mmW frequencies will be done using OTA measurements.

Wavelengths of currently used LTE systems are from 700 MHz (42.9 cm) to 3.5 GHz (8.5 cm), and at 27 GHz mmW frequency the wavelength is 1.1 cm. The inner dimensions of the EMC chamber of the University of Oulu are 10 m x 6 m x 5 m (length x width x height). The OTA measurements are challenging at 700 MHz LTE frequencies with a typically sized telecommunication testing EMC chamber with a length of 3 m [65], since the dimension is seven wavelengths, only. New measurement methods can be developed, if the same EMC chambers are used for mmW frequency measurements since these EMC chambers enable long-range RF measurements at mmW frequencies. A 3 m test range at 27 GHz corresponds to 270 wavelengths. If a similar test range is applied to 700 MHz testing, then a chamber more than 115 m in length would be needed. The usage of current EMC chambers at mmW frequencies opens opportunities to perform macro-scale OTA testing within the chamber. Alternatively, dedicated EMC chambers for mmW measurement purposes may be significantly smaller than when used with LTE frequencies, for example, 1 m x 2 m x 1.5 m [66].

One important aspect of OTA testing is that tests need to be performed in far-field conditions. A radio unit, which is larger than the integrated radiating antenna element or the antenna array, may have a far-field threshold distance outside the EMC chamber. Measurement orientations of UEs are specified in [67] and possible UE device antenna locations are shown in [68]. The size of the UE or the maximum distance between radiators should be used as dimensions when calculating minimum far-field measurement distances [67, 68]. If a 5G mmW BTS unit includes an active antenna system, then the far-field may be larger than a room-sized EMC-chamber installation [68]. The far-field distance or the Fraunhofer distance can be calculated as [69]:

\[ d_F = \left( \frac{2D^2}{\lambda} \right), \]  

where \( \lambda \) is the wavelength of the operational frequency in free space, and \( D \) is the largest physical linear dimension of the antenna, the antenna array, or the radio unit when antennas are integrated into the radio unit. The far-field distance of the antenna array
module 90 x 34 mm (Length x Width) used with the PoC radio was 1.8 m at 28 GHz [31].

A photograph of the full radio configuration of the developed 5GChampion system and the physical dimensions of the radio units at one link end are shown in Fig. 14. The full configuration includes two radio units, which both have two antenna arrays. In the full configuration, each antenna module [31] can be considered to be an antenna element in a larger antenna array. Thus, the far-field distance for each operational condition changes based on the activated radio array transceivers. If one array transceiver in one
If the radio unit is activated, then the far-field distance is the previously mentioned 1.8 m at 28 GHz. If both radio transceivers or both antenna arrays are activated, then the diagonal of the antenna arrangement is 25 cm, as shown in Fig. 14 with dimension label 5 and the far-field distance is 11.7 m as shown in Fig. 15. If the radio unit would operate as a reflector for the antenna array or the radio unit can be considered to influence the radiation, then the diagonal of 67.8 cm of the radio unit would be the largest dimension of the array and the far-field distance reach would be up to 85 m. In the case of two radio unit operations, marked with labels 6 and 7 in Fig. 15, the far-field distances are a staggering 295 m and 303 m, respectively.

5G mmW BTS RF performance testing should be performed in far-field conditions to mimic virtual drive testing [70]. The OTA testing of the BTS should mimic real-life conditions, requiring a fading channel between UE and BTS. The signal can be faded with a fading channel simulator, and the measurement can be performed in the EMC chamber with multiple testing probes [70]. A combined 5G UE and BTS OTA testing with fading channel capability with two EMC chambers has been proposed in [71]. In this case, a 5G BTS is located inside a dedicated EMC chamber, and the UE is in

![Fig. 15. Far-field distances of 5GChampion radio units with different radio configurations.](image-url)
its own EMC chamber. A radio channel emulator between the chambers provides an alternating radio channel environment for the link.

A two-stage OTA measurement method for fading channel measurements has been proposed in [72]. In this proposal 5G UE testing is done in two stages: In the first phase, radiated far-field UE beam patterns are measured. In the second phase, the RF performance is measured either with a line of sight RF measurement or with faded RF signals. This method is applicable both for UE and BTS. The BTS antenna array pattern measurements can be done in the near-field, and the results can be converted to corresponding far-field values [73].

3.2 OTA measurement of the radiated TX power of a 5G mmW radio

The generation of radiated transmission power with electrical beam steering of an antenna array transmitter is illustrated in Fig. 16. The maximum effective isotropic radiated power (EIRP) of a 5G mmW PoC can be calculated following when identical TX paths are assumed

\[ EIRP = P_{PA} + 10 \log_{10}(N_{PA}) - IL_{Post \, PA} + G_{ant} + G_{array}, \]  

(2)

where \( P_{PA} \) is conducted power from the last power amplifier (PA), \( N_{PA} \) is number of parallel PAs in the array, \( IL_{Post \, PA} \) represents the series losses between last PA stage and antenna element, and \( G_{ant} \) is antenna gain of the antenna element compared to isotropic radiator. The \( G_{array} \) is the array gain in the intended beam direction, where \( N \) signals from different transmission paths are summed perfect coherently and the coherence gain can be approximated as \( 10 \log_{10}(N) \). In the example in Fig. 16, the EIRP 59.7 dBm is calculated with the assumptions used in [1]. The direction of the TX beam can be controlled with electrical beam steering implemented using digitally controlled phase shifters in each TX chain.

The level of RF radiation on human tissue is measured with a specific absorption rate (SAR) value, which is expressed with the unit W/kg. Mobile device manufacturers need to provide information on the SAR value to the end-customer. Regulatory authorities carry out confirmation SAR tests. Such measurements have been performed for each mobile phone model on the market in Finland from spring 2003 onwards [74]. The SAR value is measured from the proximity of the radio device to emulate the use-case where the device is near the human body. The European Union requirement is 2.0 W/kg averaged over 10 g of tissue [75], while in US the requirement is 1.6 W/g averaged over
It has been considered in [77], that SAR is not the best measure for the absorbed energy at the frequencies beyond 10 GHz, since the depth of penetration into the tissue is small, and the incident power flux density of the field (in W/m^2) is a more appropriate dosimetric quantity.

The intent power flux is used if the device is not intended for use in proximity to the human body i.e. base stations, RF relay stations, and wireless backhaul units. The RF power flux density $S$ of the radiation can be calculated as [76]

$$S = \left( \frac{PG}{4\pi R^2} \right) = \left( \frac{EIRP}{4\pi R^2} \right),$$

where $P$ is the input power to the antenna, $G$ is the gain of the antenna compared to omni-directional antenna, $EIRP$ is radiated transmission power in mW or in W towards the main lobe of the antenna and $R$ is the measurement distance from the center of the radiator in cm or m. The unit of $S$, is for example, mW/cm^2 or W/m^2, and it can be noticed from (3) that the power flux density is independent of the operational frequency.

There are electromagnetic field (EMF) regulatory requirements for public and occupational exposure up to 300 GHz in [78, 76]. The maximum limit for the power flux density for an occupational person (who knows that the RF transmission is on)/controlled

![Diagram](image)

Fig. 16. An example of the EIRP calculation of an array transmitter with beam steering.
Fig. 17. Safety limits for different radiated power levels and the measured 5G PoC EIRP=45 dBm shown with a bold curve.

exposure is 5 mW/cm² for frequencies between 2.0 GHz and 300 GHz. The maximum limit for the power flux density is 1.0 mW/cm² (or 10 W/m²) for frequencies between 2.0 GHz and 300 GHz for the general public/uncontrolled exposure [78, 79]. A summary of the calculated radiated power flux densities with safety distances are shown in Fig. 17.

The TX signal attenuated in the LOS channel with a free space path loss (FSPL) [69]

\[ FSPL = \left( \frac{4\pi d}{\lambda} \right)^2. \]  

(4)

where \( \lambda \) is the wavelength of the operational frequency in m and the \( d \) is measurement distance in m. The FSPL is typically used on a dB scale in RF calculations or FSPL(dB) = \( 10\log_{10}(FSPL) \). The radiated EIRP power level is attenuated with FSPL, according to (4) and the attenuated EIRP signal P(dB) can be written as

\[ P(dB) = EIRP(dB) - FSPL(dB). \]  

(5)
Previous equations (3), (4) and (5) can be combined and the power flux density at
distance R can be written as

\[ S = \left( \frac{10^{P_{dB}/10}}{4\pi R^2} \right). \]  (6)

The measured EIRP level is 45 decibel compared to mW (dBm) for the 5G mmW
PoC [VIII], and 23 cm, and 50 cm safety limits are calculated based on (6). Safety
distances for multiple EIRP values are presented for occupational personnel and the
general public in Fig. 17. The calculated safety distances are within the far-field distance
of the antenna array of the 5G mmW PoC. There is fluctuation in the power levels in the
near-field, since the TX is not formed as a planar wave.

These values are in line with RF safety limits of 0.2 - 3.0 m proposed by mobile
manufacturer forum for sector coverage base stations [79]. The wireless backhaul units
are typically designed to be used in an open area where there are no persons close to the
unit. The maximum EIRP for mmW operation has not been clearly specified in the 5G
NR release 15 [16], and the maximum EIRP is not limited in release 16 [80]. The 3GPP
standard simulations for the integrated backhaul system-level simulations have used
68 dBm EIRP and a 10 m height for the micro BTS [37]. The calculated safety limits for
the 68 dBm EIRP are:3.2 m for occupational persons and 7.1 m for the general public.

Previous safety limits are frequency agnostic, and if signal attenuation is taken into
account, then the transmission is attenuated to a 7.1 m distance at 28 GHz by 78.4 dB,
and the signal power level is -10.4 dBm or 0.1 mW based on (6), which is significantly
less than expected 1.0 mW/cm² [78, 79]. Alternatively, if the safety distance is defined
based on a realized power 1.0 mW level from the EIRP 68 dBm at 28 GHz, the safety
distance would be reduced from 7.1 m down to 2.1 m.

3.3 OTA measurement of the signal beam width

The measurement and verification philosophy in 5G and especially 5G mmW standards
has changed from earlier telecommunication standards, since all RF performance
measurements are performed with OTA measurements. [16, 24]. Similarly, the
measurement philosophy in the EMC-chamber measurements has changed from the idea
of "how good is the signal?" to "where is my signal" mmW measurements [81]. The 5G
mmW OTA measurements need to be performed in an agile manner, since directive TX
and RX beams are steered during the measurements.
A block-level diagram of the OTA measurement setup supporting beam steering is shown in Fig. 18. This setup has been used to measure the TX and RX signal levels and the system EVM performance over beam steering angles. The 5G test signal waveform following the 3GPP 5G NR standard [16] was generated using the Keysight M8190A arbitrary waveform generator (ARB) as shown in Fig. 18. The ARB was connected to an RF signal generator (RF gen) Keysight E8267D PSG using a differential IQ signal for the up-conversion to RF, or for the down-conversion to an intermediate frequency (IF). The EVM was measured with a Keysight N9040B (UXA) digital signal analyzer and analyzed with the Keysight 89600 VSA software. Both EVM and RX signal power levels have been stored for each TX test signal levels at each steering angle.

The used OTA measurement system mainly concentrate on the horizontal antenna pattern measurements since the elevation adjustment capability of the system is limited. For a full three dimensional (3D) antenna pattern measurement, a 6-axis robotic arm has been proposed in [82]. The proposed robotic-arm-based 3D-measurement system can be upgraded to a 3D-interference measurement system if the second arm is equipped with an interference signal source.

The most widely used signal beamwidth definitions are a half-power beamwidth (HPBW) and a first null beamwidth (FNBW), which are illustrated in Fig. 19(a). The RF measurements to validate beam patterns are typically done with a continuous wave, which has a constant envelope. For varying amplitude modulations, the beam patterns
will start to limit the usable beamwidth (Bw) for the communication. A new metric EVM beamwidth has been proposed based on EVM measurements. The measured EVM is compared to the maximum system EVM value for the modulation which is good enough for successful communication, and the EVM Bw is the maximum beamwidth of successful communication. In practice, this varies and should be defined separately for any modulation and coding scheme.

An approximation of a theoretical -3 dB beamwidth $\Theta$ can be calculated with a known antenna gain $G$ using

$$\Theta \approx 2\sqrt{\frac{\pi}{G}}$$

where the array gain $G$ is a linear number, and $\Theta$ is in radians [69]. The measured 5G mmW PoC antenna array gain is 20 dB [31], i.e. 100 on a linear scale. Thus, the calculated -3 dB beamwidth is 20.3° or $\pm 10.2°$ for the implemented 5G mmW antenna array [31]. Similar antenna arrays have been used in both the RX and the TX units in all OTA power and EVM performance measurements. This -3 dB beamwidth is the maximum theoretical beamwidth that can be achieved. The implemented and measured -3 dB Bw is narrower than calculated from (7), since in antenna arrays, some part of the main beam power leaks into the sidelobes due to non-idealities. The power leakage narrows the main beamwidth, and the -3 dB Bw or the HPBW is $\pm 3$ degrees around.
Fig. 20. Measured RX signal power at the output of the RX array with 5G NR 16-QAM modulated signal with applied beam steering 0 degree, reprinted by permission Paper [VIII] ©2019 IEEE.

the target steering angle. The FNBW is ±7 degrees regardless of the received signal power level in Fig. 20. The first measured sidelobe levels of the system are -12.0 decibel compared to carrier (dBc) and -14.0 dBc, and second side lobes are -15.7 dBc and -12.3 dBc, as shown in Fig. 20. It should be noted that the radiated received signal power has been marked with received effective isotropic received power in Fig. 20.

The requirements of the EVMs for the TX only and full system EVM are shown in Fig. 21. A summary of measured main beam widths with different modulations is shown in Fig. 22. It can be seen from the results that the Bw and the cell coverage of successful communication vary based on the used modulation since different modulations require different signal-to-noise ratio (SNR), which leads to different shapes between cell coverages. This phenomenon can be called beamwidth breathing. A similar problem was faced with 3G code division multiple access (CDMA) systems when adaptive coding rates were used for different user data rates. The changing coding gains changed the cell coverages of the CDMA cells, and this was called cell breathing [83]. The mentioned beam and cell breathings are illustrated in Fig. 23.
3.4 OTA noise figure measurement of mmW receiver

The noise figure of the receiver is one of the most critical parameters to be evaluated from any receiver. It has a direct impact on the range of the wireless link. The NF of any receiver can be defined using the SNR ratios of the input and output of the RX, where NF degrades the input SNR to the output SNR.

A block diagram of an ideal array receiver is shown in Fig. 24. The NF’s definition for a phased array receiver is more complicated than for a single path RX because it depends on the definition of the input SNR. The noise analysis of the array receiver can be divided into parallel and common path noise contributions. Each RX path has its NF before the combination point, and the phase-coherent combining of RX signals increases the total received signal level at the combination point. In contrast, noise signals with random phases are combined incoherently or as a power combination. The coherence gain of an RX array is an SNR improvement, where the SNR can be ideally improved by N times or $10\log_{10}(N) \text{ dB}$ compared to a single RX path, where N is the number of RX paths in the array. Mathematically infinite RX paths would lead to a physically not
Fig. 22. Measured modulation beam widths from the 5G mmW PoC, reprinted by permission Paper [VIII] ©2019 IEEE.

Fig. 23. Comparison of 3G cell breathing and 5G beam breathing.
unfeasible situation where the calculated NF of the RX array would be negative on the dB scale. This effect is compensated by a correction factor that keeps the NF always above zero [19]. The RX signals are steered in the direction of the incoming signal by adjusting the phase rotator values in each RX path so that the output of the array signal level is maximized. The common path is the RX signal path after the last coherence combination node.

The conducted received signal level $P_{RX\_out}$ at the output of the array receiver can be calculated as follows

$$P_{RX\_out} = RXEIRP + G_{ant} + 10\log_{10}(N_{RX}) - IL_{Pre\_LNA} + G_{coherence} + G_{RX}, \quad (8)$$

where RX EIPR is the OTA signal level in the input of the RX antenna, $N_{RX}$ is number of parallel RX paths in the array, $IL_{Pre\_PA}$ is the combined series loss before the first low noise amplifier (LNA) stage, and antenna element, $G_{ant}$ is the antenna gain of the antenna element compared to the isotropic radiator and $G_{RX}$ is the conducted gain of the whole RX path. The main difference between the TX and RX signal level analysis of the array is that the array signal combination is done in TX in OTA. In RX, the combination is performed with electrical components. In practice, the combination with electrical components is lossy and prone to phase variations leading the RX coherence gain to below the theoretical value. In contrast, the OTA combination is closer to the ideal combination.

The conducted coherence gain of two RX paths of the 5G mmW PoC RX array has been measured with different signal bandwidths and these are shown in Table 3. The content of the table 3 is from Paper [I]. It can be seen that the conductive
Table 3. Coherence gain using 16-QAM modulation.

<table>
<thead>
<tr>
<th>Signal bandwidth</th>
<th>100 MHz</th>
<th>200 MHz</th>
<th>400 MHz</th>
<th>800 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherence gain</td>
<td>2.7</td>
<td>2.1</td>
<td>2.3</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Coherence gain with two almost equal gain RX paths is close to the theoretical 3 dB. The implementation losses are caused by component-to-component variations, integrated circuit (IC)-manufacturing, and packaging process variations. Some implementation losses are related to PCB design. It is not possible to make the signal lines entirely similar on a multilayer PCB, and the PCB layout is not perfectly symmetrical [I]. The conducted coherence gain measurement was limited to two RX chains, only due to the lack of laboratory RF combiners supporting mmW frequencies.

The NF of the RX can be measured by observing the noise level raise at the output of the RX. The simplest method is to use a noise source which generates white noise with a known noise level. The measurement can be taken on the noise level on the dBm scale or with noise temperature, which is discussed in detail in [20]. Operational frequencies of currently available noise sources are limited to 50 GHz and noise levels to 12 dB [25]. However, this equipment has limitations when wide signal bandwidths are measured since the measurement equipment noise level limits the measurement dynamic with low NF receivers. An alternative is to measure with a narrow measurement BW, but this is not the correct operation for a mmW RX designed for wide channels BWs. The measured frequency response of 5G mmW PoC RX is not smooth [I] [IV], and thus a noise-source-based NF measurement is not an optimal solution. A noise-source-based measurement is a conductive measurement, which is not optimal for the 5G mmW array receiver, since all RF performance measurements should be performed with OTA measurements. An effective noise figure measurement measurement with OTA has been recently proposed in [21], where the effective NF of one branch is calculated. The NF of the whole array is conductively measured with CW, which is a very narrow BW measurement, and thus it is not representative of the wideband operation.

The main drawback of a narrowband NF measurement is that it correlates with a single sub-carrier BW and gives the sub-carrier NF performance. The narrowband performance may differ significantly from the wideband performance if there are sharp notches in the frequency response within the wideband 5G channel. A narrowband noise-source-based NF measurement is performed with a high RX input signal power level, where the gain of the RX can be obtained. Then, the noise is feed to the receiver and the noise level is measured at the output of the receiver. The amplified noise level is...
compared to the noise level from the noise source, and the difference gives the NF of the receiver.

Physical component or PCB dimensions, errors during the manufacturing or component parameter variations may create unwanted frequency resonances. Additionally, wide BW measurements emulate the real mmW radio operational conditions which the mmW RX will face under typical operation. Previously proposed OTA NF measurements have been performed close to the system noise level, which introduces uncertainty to the measurement result. Thus, it is advantageous to perform the NF measurement at high signal levels to maximize the measurement range. The proposed NF measurement method based on the EVM measurement of the 5G communication signal can be performed in manufacturing and R&D facilities with currently available
RF measurement equipment [I]. A summary of different NF measurement systems is shown in Fig. 25 and the new proposed NF measurement method is the method c.

A new NF measurement method for 5G mmW phased RX array shown in Fig. 25 has been proposed in [I] and analyzed in [VII][VIII], which is based on OTA measurement of EVM. The EVM based NF measurement is performed as follows: first an EVM measurement is performed by transmitting the measurement signal OTA to the 5G mmW array receiver. Then the RX signal is demodulated at the output of the RX by the measurement equipment. The EVM measurement is performed at multiple RX input power levels in order to form an EVM ‘path curve’ or RX input power-dependent EVM curve. The measured EVM curve from the RX of the 5G mmW PoC is shown in Fig. 26.

The light blue curve models the noise level raise due to the NF in the EVM curve. The EVM has the following direct relationship to the received signal SNR [84][I]:

$$SNR = P_{outRX} - P_{Noise} = -20 \cdot \log_{10} \left( \frac{EVM\%}{100} \right), \quad (9)$$

where $P_{outRX}$ is the input RX signal level and $P_{Noise}$ is the total noise level seen by the RX which is a sum of the thermal noise and the NF of RX:

$$P_{Noise} = P_{th} + NF, \quad (10)$$
where $NF$ is the noise figure of the receiver, $P_{th}$ is the thermal noise level on the RX channel i.e. $-174$ dBm/Hz + $10 \cdot \log_{10}(BW)$, where $BW$ is the signal BW in Hz. The EVM performance due to the NF RX array can be calculated based on Eqs. (9) and (10) and result is shown in Fig. 26. It can be seen from Fig. 26 that the NF affects the EVM performance from the optimal signal levels downwards and limits to sensitivity of the receiver. The modulation of the signal has an effect on the EVM performance. The EVM performance is limited to a finite level due to the fixed range of analog-to-digital (ADC) converters, phase noise and other signal independent non-idealities in the measurement equipment.

The initial link budget for the 5G PoC mmW system is shown in Fig. 36. The sensitivity of the 5G mmW PoC RX has been calculated using

$$RX_{sens} = P_{th} + SNR_{RX, out} + NF_{array},$$

(11)

where $P_{th}$ is the thermal noise level in dBm, $SNR_{RX, out}$ is the required SNR at the output of the RX and $NF_{array}$ is the noise figure of the array receiver.

The NF of the 5G mmW PoC has been OTA measured, modeled, and calculated based on Eqs. (9) and (10) in dB and linear scales. The calculated NF of the 5G mmW PoC is 5.0 dB on both scales, and this value corresponds well with the RF system-level calculated NF of the RX array [IV] [VIII]. The effect of the component parameter variations have been simulated in RF system-level calculations, and the summary of the results is shown in Fig. 27. The simulation, with the minimum and maximum value of the RX components, shows, that the NF of the RX array follows a skewed distribution where the longtail leans towards high NF values. The measured NF value of 5.0 dB is better than the calculated nominal NF value of 5.6 dB. The NF would start to follow the simulated skewed distribution, if the RF design was produced in high volume production.

### 3.5 OTA EVM measurement of the 5G mmW transceiver

The initial plan for the testing of the prototype (5G mmW PoC) was to use conductive tests. After the single path RX gain measurements and the coherence gain measurement of two RX chains [IV], all of the following tests were performed using OTA testing. The complexity of the cabling and lack of RF laboratory RF signal splitters were primary reasons for OTA testing of all RF parameters.
Fig. 27. RF system analysis of NF of array receiver based on component to component variations from data sheets with maximum coherence gain, reprinted by permission Paper [VIII] ©2019 IEEE.

System-level error vector magnitude is a combination of TX and RX EVMs [56]. In the LTE system, the EVM is measured only at the highest transmission power level according to the standard [15]. The RX EVM is used as a design parameter for the RX signal path, and this was validated via a bit error rate (BER) or block error rate (BLER) measurements. However, the relationship between BER/BLER and RX EVM is a non-linear function depending on the used signal modulation, coding, digital signal processing algorithms, and RX signal level. The EVM gives a more consistent measure of the RF performance than the BER or BLER. The system EVM performance of the mmW system in an indoor scenario with multiple beams has been studied in [56].

The total measured system EVM value is a combination of TX and RX EVMs, and the contribution of the EVM of the measurement system. If the EVM contributions are uncorrelated, which is a valid assumption in most of the cases, then the EVM contributions can be combined as [VIII]

\[
EVM_{\text{system}}(P_{\text{RX}}, P_{\text{TX}}) = \sqrt{EVM^2_{\text{TX}}(P_{\text{TX}}) + EVM^2_{\text{RX}}(P_{\text{RX}}) + EVM^2_{\text{RF equip}}}, \quad (12)
\]
Fig. 28. EVM measurement block diagrams: (a) reference conducted EVM, (b) reference OTA, (c) TX EVM only, (d) system EVM in EMC chamber, and (e) system EVM in EMC chamber with absorber tile, reprinted by permission Paper [VIII] ©2019 IEEE.

where $EVM_{TX}$, $EVM_{RX}$ and $EVM_{RF\text{ equip}}$ are the EVMs of TX, RX, and the measurement system, respectively. $P_{TX}$ is the transmission power level, $P_{RX}$ is received signal level and EVM is a function of the transmission and reception signal levels. $EVM_{RF\text{ equip}}$ is a combined performance of the measurement system (signal generation and analysis) that is measured using signal levels at the input and output of the DUTs [VIII]. It is assumed that signal levels over the measured power ranges remain within the constant EVM performance range of the measurement equipment.

The system EVM measurement was performed for the boresight of the radio unit with and without electrical beam steering. The proposed system EVM measurement flow is shown in Fig. 28. First, the conducted reference EVM of the measurement system was verified. The conducted EVM for the system was 0.446% at 4 GHz IF frequency and 1.776% at 28 GHz for the measurement setup shown in Fig. 28(a). An additional OTA
contribution to the measurement system EVM was measured, as shown in Fig. 28(b) and the contribution is 2.60% due to e.g. channel estimation, equalization and compensation filtering inside the UXA, and potential signal reflections of the EMC lab. Next, the standalone EVM of the TX was measured, as shown in Fig. 28(c). In the standalone TX EVM measurement, the OTA and conducted EVM contributions were subtracted from the TX EVM measurement result, so that TX EVM only contribution was validated. The RX EVM performance verification followed after the TX EVM measurement, as shown in Fig. 28(d). The RX EVM can be calculated from the measured system EVM results with (12) by subtracting the conducted, OTA, and TX EVM contributions. Finally, the applicability of the automatic gain control (AGC)-based signal level variation is verified with an absorber tile measurement, and the measurement setup is shown in Fig. 28(e) [VIII].

Statistical measurement system analysis (MSA) is used to validate the repeatability of the measurements and to analyze the impact of the measurement environment to the results. A commonly used method to quantify the measurement error of a gage is to use the gage repeatability and reproducibility (Gage R&R) measurement [85]. The Gage R&R method is based on variance analysis, and it can determine variations from the total measured variance introduced by parts, operators, and measurement repeatability. Mathematically it can be expressed as [85]

$$\sigma^2_T = \sigma^2_P + \sigma^2_O + \sigma^2_R,$$

where $\sigma^2_T$ is the total observed variance of the measurement results, $\sigma^2_P$ is the variance of the measured DUTs, $\sigma^2_O$ is the variance due to the operator (or equipment) and $\sigma^2_R$ is the variance due to repeatability. The MSA analysis for the OTA EVM measurement within the EMC chamber was done with two operators, with three sets of 12 repeated measurements at one-hour intervals. One DUT was measured with the same measurement system and with the same system configuration leading the DUT contribution $\sigma^2_P = 0$ in (13). The total observed measurement error in the EVM measurement due to operators and repeatability was $\sigma_T = 0.042\%$. When the measurement error is compared to the minimum measured EVM value 3.90% then the error is 0.042% / 3.90% = 1.07% [VIII], which is significantly better than the threshold value 10% for a good quality measurement system [85].

IEEE standardization has a working group to study uncertainty of EVM with modulated signals, namely: "Trial-Use Recommended Practice for Estimating the Uncertainty in Error Vector Magnitude of Measured Digitally Modulated Signals for
An overview of possible measurement interfaces that can be used for system EVM measurements is presented in Fig. 29. The system EVM measurement is performed on the RX side of the link, since the 3GPP standardizes the TX side performance. The system EVM measurement can be done either from analog or digital interfaces. An analog interface gives the option that any measurement device can be used for the measurement. If the measurement is performed with digital signals, then only the chipset developer or the system integrator can access the digital interface and the digital data.

The system EVM measurements were performed with a 5G NR 100 MHz wide test signal, which were modulated with 16-QAM, 64-QAM, and 256-QAM modulations. Measurements were performed over $\pm 15^\circ$ steering angles, and a 16-QAM system EVM measurement result is shown in Fig. 30. The optimal system EVM performance signal range is from -40 dBm to -70 dBm in the Fig. 30. The RX limits the system performance when the input signal level is higher than -40 dBm, since the TX overdrives the dynamic range of the RX. The system EVM performance is noise limited when the RX input level is below -70 dBm.
Fig. 30. 16-QAM system EVM measurement single beam result with 5 degrees steering, reprinted by permission Paper [VIII] ©2019 IEEE.

Fig. 31. Beam steering cell ranges for 16-QAM based on EVM measurement results with 40 dBm EIRP, reprinted by permission Paper [VIII] ©2019 IEEE.
The OTA EVM measurement of the 5G mmW PoC, with a fixed TX power and with an attenuated RX input signal level, gives an excellent indication of the operation of the wireless link. The RX signal level is attenuated in the RX unit by using the digitally controlled step attenuators in the RX signal path. If the directions of the TX and the RX beams of the 5G mmW PoC are steered in 2-D (x-y direction), the coverage can be estimated. The beam steering capability in the TX and the RX units is limited, and the TX and the RX units are placed at the same level to secure the OTA link in the elevation direction. The system EVM performance of a 5G NR 16-QAM with the beam steering capability as expected coverage is shown in Fig. 31. The electrical beam steering has been done for the RX DUT from -15 degrees to +15 degrees in 5 degrees steps with 1-degree of physical rotation. A complete EVM performance measurement over the steering angles took tens of hours to perform with the used granularity. The measured coverage estimation would be smoother if the same physical and electrical steps would have been applied, but the measurement time would have been five times longer than current.

### 3.6 5G mmW OTA RX linearity measurement

The linearity of the receiver determines how much 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 merits of linearity of the receiver is the third-order intercept point (IP3) [87].

![Third order IMD measurement with a CW and modulated signal](image)

**Fig. 32.** Third order IMD measurement with a CW and modulated signal, reprinted by permission Paper [III] ©2018 IEEE.
The third order linearity can be measured with a two-tone intermodulation distortion (IMD) test, which is shown in Fig. 32. Two CW test signals at frequency offset ($\Delta f$) are fed into the RX, and signal levels of the mixing products $\Delta f$ frequency apart from the test signals are measured. This two-tone measurement method is used for linearity measurement of array receiver in [88]. The input IP3 point (IIP3) can be calculated as [87]

$$IIP3 = \left( \frac{1}{2\Delta IM3} \right) + P_{CW},$$

where $P_{CW}$ is the power of one CW test signal, and $\Delta IM3$ is a power difference between the mixing product and one CW test tone signal. The CW signal is an not optimal test signal for a wideband receiver, and a modulated test signal is preferred, especially when studying in-band linearity. In the out-of-channel case, non-linearity standard tests are typically done with one modulated and one CW signal. The IP3 testing was performed with a digitally modulated 100MHz 16-QAM modulated test signal with a roll-off factor of $\alpha=0.35$. The power of the modulated test signal may be considered to be shared with two CW test signals in the two-tone test, and (14) is modified for the modulated signal case, so that $P_{CW} = P_{\text{Mod}} - 3$dB. The test signal was transmitted over-the-air to the antenna array of the 5G mmW receiver at a frequency of 26.5 GHz. The receiver signal paths of the 5G mmW array receiver were phased so that the main lobe of the antenna array pointed towards the test antenna.

A spectrum at the output of the 5G array receiver was measured, and one of the measurement results is shown in Fig. 33. The test signal in the measurements was a 16-QAM modulated 100 MHz wide signal with an $\alpha$ of 0.35. The level of the test signal was varied, and a summary figure of the linearity measurement results is shown in Fig. 34. 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. 34. The first LNA dominates the linearity of the array receiver, and the IIP3 specification of the LNA is -4.0 dBm. The third-order non-linearity expects that the slope of the 3rd order IMD product is 3:1. Our measurement results show that the slope of the 3rd order IMD is 2.4, which is a good match with the theoretical value.
Fig. 33. Measured spectrum of the received signal with the RX ACP clearly visible, reprinted by permission Paper [III] ©2018 IEEE.

Fig. 34. Linearity measurement of array receiver in the main beam direction, reprinted by permission Paper [III] ©2018 IEEE.
3.7 5G mmW OTA link range estimation

The link range of the 16-QAM modulation for the 5G mmW PoC radio was estimated during the system design phase of the PoC project. The original link range estimation spreadsheet is shown in Fig. 36, where the conducted TX power from the individual path was 30 dBm, and the radiated TX power was estimated to be 60 dBm. The unwanted resonances in the PoC radio implementation prevented the operation of the radio board at the highest TX power levels. Thus the measured maximum TX EIRP power was 45 dBm in [VIII] [IX].

An exponent of the free space path loss as shown in (4) can be varied to better model different physical environments. The path loss exponent $\alpha$ varies from the free space value of 2.0 to the sub-urban value of 3.3 [89] and, thus, the loss of the signal path (PL) can be written as [89]

$$PL = \left(\frac{4\pi d}{\lambda}\right)^\alpha,$$

where $\lambda$ is the wavelength of the operational frequency in m and the $d$ is a distance in m. The PL is typically used on a dB scale or the $PL(dB) = 10\log_{10}(PL)$.

---

Fig. 35. Cell area estimation based on system EVM measurements, reprinted by permission Paper [VIII] ©2019 IEEE.
A path loss exponent of 2.5 was used in Fig. 36, which is higher than the value of 2.0 for the free space loss. There was the uncertainty as to how well the mm frequencies would follow the free space path loss model at the time of the system analysis of the PoC, and a high path loss coefficient was used to have a conservative estimate of the radio link range.

The link range estimations have been revised in the thesis based on the measurement results presented in Papers [I],[IV],[VIII],[VII] and [IX]. The revised link range estimations of the 16-QAM, 64-QAM and 256-QAM are shown in Tables 4, 5 and 6, respectively. The updated link range calculations have been done with an EIRP of 40 dBm, which was used in the EMC-chamber OTA measurements. The system link range estimations have been performed based on an system EVM performance analysis, RF system-level calculations, and OTA EVM measurements. The system EVM values for the TX and RX, and corresponding SNRs are presented in [VII] and [IX].

A good agreement with the calculated RF system calculated and two different measurement methods of the sensitivity for the RX array can be seen in Tables 4, 5 and 6. For example, the RX system calculated sensitivity, the OTA EVM measured sensitivity and the calculated RX array sensitivity based on measured parameters values are within one decibel with the 16-QAM modulation.

The estimated link distance based on RF system calculation is in good agreement with link ranges based on OTA EVM measurements and measured parameter based estimations. All link range estimations are within 6% range with the 16-QAM modulation and within 17% with 64-QAM modulation. The link range of 256-QAM modulation has the largest link range deviation of 30%. However, the PoC radio was not originally designed to support this kind of high level modulation, and for this reason, the signal path was not optimal for this modulation. The developed 5G mmW radio platform was one of the first which have reported 5G 256-QAM modulation OTA performance in the 28 GHz frequency band in [VIII].

The cell area coverage estimations based on OTA measured system EVM results for three studied modulations are shown in Fig. 35. The link range estimations for 16-QAM modulation are based on the measurement results shown in Figs. 30 and 31. The ripple in the cell area estimations is significant Fig. 35, but this is due to the measurement set-up since the beam has been electrically steered in 5 degrees steps to reduce the measurement time. The developed 5G mmW radio is capable of steering the beam at a granularity of 1 degree granularity [90]. If the beam steering is done with fine granularity, then the coverage area will be smooth without nulls in the cell coverage area.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of antenna elements or antenna array gain</td>
<td>16</td>
<td>N/A</td>
</tr>
<tr>
<td>Gain of antenna element</td>
<td>10.72</td>
<td>dB</td>
</tr>
<tr>
<td>SNRmin</td>
<td>25.20</td>
<td>dB</td>
</tr>
<tr>
<td>SNRmin_coded</td>
<td>24.49</td>
<td>dB</td>
</tr>
<tr>
<td>Transmitter (TX) EVM</td>
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<td>dB</td>
</tr>
<tr>
<td>RX SNR Requirement (D – E on linear scale)</td>
<td>29.83</td>
<td>dB</td>
</tr>
<tr>
<td>Noise density</td>
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<td>dBm/Hz</td>
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<tr>
<td>Thermal noise power over channel</td>
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<td>dBm</td>
</tr>
<tr>
<td>Receiver (RX) noise figure</td>
<td>10.00</td>
<td>dB</td>
</tr>
<tr>
<td>Sensitivity of one receiver (F + H + I)</td>
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<td>dBm</td>
</tr>
<tr>
<td>Conducted transmission power of each transmission path</td>
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<td>dBm</td>
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<tr>
<td>Antenna gain transmitter (A + B)</td>
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<tr>
<td>Antenna gain receiver (A + B)</td>
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<tr>
<td>Maximum distance</td>
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Fig. 36. Designed link budget of the 5G mmW PoC with a 64-QAM modulated 100 MHz signal bandwidth, reprinted by permission Paper [I] ©2018 Wiley.
<table>
<thead>
<tr>
<th>Row</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td># of antennas in array</td>
<td>16/12.0</td>
<td>lin/dB</td>
<td>[IV]</td>
</tr>
<tr>
<td>B</td>
<td>Gain of antenna element</td>
<td>9.1</td>
<td>dB</td>
<td>[IX]</td>
</tr>
<tr>
<td>C</td>
<td>Modulation BW</td>
<td>98</td>
<td>MHz</td>
<td>[I][VII]</td>
</tr>
<tr>
<td>D</td>
<td>Noise density power</td>
<td>-174.23</td>
<td>dBm/Hz</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Thermal noise at BW</td>
<td>-94.3</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Wavelength @ 28 GHz</td>
<td>10.71</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>System EVM requirement</td>
<td>17.70</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>H</td>
<td>System SNR requirement</td>
<td>15.04</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>I</td>
<td>Transmitter (TX) EVM</td>
<td>3.0</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>J</td>
<td>TX SNR</td>
<td>30.46</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>K</td>
<td>Receiver (RX) EVM</td>
<td>17.4</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>L</td>
<td>RX SNR</td>
<td>15.17</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>M</td>
<td>Conducted one TX path</td>
<td>9.0</td>
<td>dBm</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>N</td>
<td>TX ant. gain (elem. + array)</td>
<td>21.0</td>
<td>dBi</td>
<td>[IX]</td>
</tr>
<tr>
<td>O</td>
<td>TX FE losses</td>
<td>2.0</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>P</td>
<td>TX measurement accuracy</td>
<td>0.0</td>
<td>dB</td>
<td>[VIII][II]</td>
</tr>
<tr>
<td>Q</td>
<td>Measured TX EIRP</td>
<td>40.0</td>
<td>dBm</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>R</td>
<td>Meas. NF of array RX</td>
<td>5.0</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>S</td>
<td>Coherence gain in RX</td>
<td>11.0</td>
<td>dB</td>
<td>[I]</td>
</tr>
<tr>
<td>T</td>
<td>RX ant. gain (element + coherence)</td>
<td>20.0</td>
<td>dBi</td>
<td>[IX]</td>
</tr>
<tr>
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<td>-74.2</td>
<td>dBm</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>V</td>
<td>Measured link margin</td>
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<td>dB</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>W</td>
<td>Path loss coefficient</td>
<td>2.0</td>
<td>lin</td>
<td>[91]</td>
</tr>
<tr>
<td>X</td>
<td>Calculated distance</td>
<td>436.8</td>
<td>m</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>Y</td>
<td>EVM OTA meas. RX sens.</td>
<td>-73.7</td>
<td>dBm</td>
<td>[VIII]</td>
</tr>
<tr>
<td>X</td>
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<td>m</td>
<td>[VIII][Thesis]</td>
</tr>
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<td>dBm</td>
<td>[VIII][Thesis]</td>
</tr>
<tr>
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<td>410.0</td>
<td>m</td>
<td>[Thesis]</td>
</tr>
</tbody>
</table>

Table 4. Link range analysis of the 5G PoC with 5G NR 16-QAM modulation.
Table 5. Link range analysis of the 5G PoC with 5G NR 64-QAM modulation.

<table>
<thead>
<tr>
<th>Row</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td># of antennas in array</td>
<td>16/12.0</td>
<td>lin/dB</td>
<td>[IV]</td>
</tr>
<tr>
<td>B</td>
<td>Gain of antenna element</td>
<td>9.1</td>
<td>dB</td>
<td>[IX]</td>
</tr>
<tr>
<td>C</td>
<td>Modulation BW</td>
<td>98</td>
<td>MHz</td>
<td>[I][VII]</td>
</tr>
<tr>
<td>D</td>
<td>Noise density power</td>
<td>-174.23</td>
<td>dBm/Hz</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Thermal noise at BW</td>
<td>-94.3</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Wavelength @ 28 GHz</td>
<td>10.71</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>System EVM requirement</td>
<td>11.3</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>H</td>
<td>System SNR requirement</td>
<td>18.94</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
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<td>I</td>
<td>Transmitter (TX) EVM</td>
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<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>J</td>
<td>TX SNR</td>
<td>30.46</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>K</td>
<td>Receiver (RX) EVM</td>
<td>10.9</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>L</td>
<td>RX SNR</td>
<td>19.26</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
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<td>M</td>
<td>Conducted one TX path</td>
<td>9.0</td>
<td>dBm</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>N</td>
<td>TX ant. gain (elem. + array)</td>
<td>21.0</td>
<td>dBi</td>
<td>[IX]</td>
</tr>
<tr>
<td>O</td>
<td>TX FE losses</td>
<td>2.0</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>P</td>
<td>TX measurement accuracy</td>
<td>0.0</td>
<td>dB</td>
<td>[VIII][II]</td>
</tr>
<tr>
<td>Q</td>
<td>Measured TX EIRP</td>
<td>40.0</td>
<td>dBm</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>R</td>
<td>Meas. NF of array RX</td>
<td>5.0</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>S</td>
<td>Coherence gain in RX</td>
<td>11.0</td>
<td>dB</td>
<td>[I]</td>
</tr>
<tr>
<td>T</td>
<td>RX ant. gain (element + coherence)</td>
<td>20.0</td>
<td>dBi</td>
<td>[IX]</td>
</tr>
<tr>
<td>U</td>
<td>Calculated RX sens. based on measurements</td>
<td>-70.1</td>
<td>dBm</td>
<td>[Thesis]</td>
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<tr>
<td>V</td>
<td>Link margin</td>
<td>110.1</td>
<td>dB</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>W</td>
<td>Path loss coefficient</td>
<td>2.0</td>
<td>lin</td>
<td>[91]</td>
</tr>
<tr>
<td>X</td>
<td>Calculated distance</td>
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<td>m</td>
<td>[Thesis]</td>
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<tr>
<td>Y</td>
<td>EVM OTA meas. RX sens.</td>
<td>-71.1</td>
<td>dBm</td>
<td>[VIII]</td>
</tr>
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<td>Z</td>
<td>Distance based EVM meas.</td>
<td>307.4</td>
<td>m</td>
<td>[VIII][Thesis]</td>
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<tr>
<td>AA</td>
<td>RF system calculated sens.</td>
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<td>dBm</td>
<td>[VIII][Thesis]</td>
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<tr>
<td>AB</td>
<td>Dist. from RF system calc.</td>
<td>255.7</td>
<td>m</td>
<td>[Thesis]</td>
</tr>
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</table>
Table 6. Link range analysis of the 5G PoC with 5G NR 256-QAM modulation.

<table>
<thead>
<tr>
<th>Row</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td># of antennas in array</td>
<td>16/12.0</td>
<td>lin/dB</td>
<td>[IV]</td>
</tr>
<tr>
<td>B</td>
<td>Gain of antenna element</td>
<td>9.1</td>
<td>dB</td>
<td>[IX]</td>
</tr>
<tr>
<td>C</td>
<td>Modulation BW</td>
<td>98</td>
<td>MHz</td>
<td>[I][VII]</td>
</tr>
<tr>
<td>D</td>
<td>Noise density power</td>
<td>-174.23</td>
<td>dBm/Hz</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Thermal noise at BW</td>
<td>-94.3</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Wavelength @ 28 GHz</td>
<td>10.71</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>System EVM requirement</td>
<td>4.9</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>H</td>
<td>System SNR requirement</td>
<td>26.2</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>I</td>
<td>Transmitter (TX) EVM</td>
<td>2.5</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>J</td>
<td>TX SNR</td>
<td>32.04</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>K</td>
<td>Receiver (RX) EVM</td>
<td>4.2</td>
<td>%</td>
<td>[VIII]</td>
</tr>
<tr>
<td>L</td>
<td>RX SNR</td>
<td>27.51</td>
<td>dB</td>
<td>[VIII]</td>
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<td>M</td>
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<td>dBm</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>N</td>
<td>TX ant. gain (elem. + array)</td>
<td>21.0</td>
<td>dBi</td>
<td>[IX]</td>
</tr>
<tr>
<td>O</td>
<td>TX FE losses</td>
<td>2.0</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>P</td>
<td>TX measurement accuracy</td>
<td>0.0</td>
<td>dB</td>
<td>[VIII][II]</td>
</tr>
<tr>
<td>Q</td>
<td>Measured TX EIRP</td>
<td>40.0</td>
<td>dBm</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>R</td>
<td>Meas. NF of array RX</td>
<td>5.0</td>
<td>dB</td>
<td>[VIII]</td>
</tr>
<tr>
<td>S</td>
<td>Coherence gain in RX</td>
<td>11.0</td>
<td>dB</td>
<td>[I]</td>
</tr>
<tr>
<td>T</td>
<td>RX ant. gain (element + coherence)</td>
<td>20.0</td>
<td>dBi</td>
<td>[IX]</td>
</tr>
<tr>
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<td>-61.8</td>
<td>dBm</td>
<td>[Thesis]</td>
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<tr>
<td>V</td>
<td>Link margin</td>
<td>101.9</td>
<td>dB</td>
<td>[Thesis]</td>
</tr>
<tr>
<td>W</td>
<td>Path loss coefficient</td>
<td>2.0</td>
<td>lin</td>
<td>[91]</td>
</tr>
<tr>
<td>X</td>
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<td>106.0</td>
<td>m</td>
<td>[Thesis]</td>
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<td>Y</td>
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<td>dBm</td>
<td>[VIII]</td>
</tr>
<tr>
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<td>m</td>
<td>[VIII][Thesis]</td>
</tr>
<tr>
<td>AA</td>
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<td>dBm</td>
<td>[VIII][Thesis]</td>
</tr>
<tr>
<td>AB</td>
<td>Dist. from RF system calc.</td>
<td>98.3</td>
<td>m</td>
<td>[Thesis]</td>
</tr>
</tbody>
</table>
4 Tolerances on 5G mmW RF, antennas and measurements

4.1 Variation in the measurement results

There is always some uncertainty in the measurements due to errors associated with the measurement event, the measurement method, the used measurement gauge, and the used resolution of the gauge. This topic has been addressed in [92], where guidelines for the measurement system analysis have been given. The measured variation can be divided into two main categories: the variation due to differences between products and the variation based on the measurement system, which is illustrated in Fig. 37.

The measurement system variation can be further divided into two categories: variation of the location of the results and the variation of the variability of the results. The variation of the location is a combination of the following parameters: The bias, which measures the difference between the observed average of measurements and the reference value. The stability measures the bias over time. The linearity measures the bias over the measurement range, if the measurement bias changes in different measurement conditions. The accuracy measures the granularity of the measurement results. All location variation parameters can be minimized with proper calibration methods, which are performed regularly.

The variability or the width of the probability distribution consists of two parameters: repeatability and reproducibility in the measurement system. The repeatability is the variation in the measurements obtained with one measuring instrument when used several times by an appraiser while measuring the identical characteristic on the same part. The reproducibility is the variation of the average of the measurements made by different appraisers using the same gage when measuring a feature on one part [92].

Part-to-part variation may result from component-to-component variation, wear-out of the manufacturing tools, differences in an assembly process, or parameter tunings. The component-to-component variation can be modeled for simulation purposes based on datasheets if commercial components are used. If components under development, e.g. PoC type 1 or technology demonstration components are used, then simulation results can be used to estimate the variability.
Fig. 37. Sources of variation in measurement results.

![Diagram of measurement system variation and part-to-part variation](image)

- **Measurement System Variation**
  - Location variation
  - Bias
  - Linearity
  - Stability
  - Accuracy

- **Part-to-Part Variation**
  - Width variation
  - Repeatability
  - Reproducibility

Fig. 38. Accuracy vs. precision (a) precision ok, but accuracy not ok (b) precision not ok, but accuracy ok (c) precision not ok and accuracy not ok (d) precision ok and accuracy ok.

Illustrations of different scenarios concerning the accuracy and precision of the measurement results or how the products have fulfilled their design targets are shown in Fig. 38. A dartboard has been used for illustration purposes, and crosses are repeated measurements or a batch of products. The bullseye is the design target or the true measurement value. The first scenario shown in Fig. 38 (a) is where the repeated measurement results are analyzed towards the known, true value, but they have a bias or a constant mean shift. The bias of the measurement is calibrated, but the repeatability of measurement is poor, which is visible with significant variation in the second scenario in Fig. 38 (b). The third scenario in Fig. 38 (c) presents a situation where the location has a constant shift with a significant variation. The best scenario is presented in Fig. 38 (d), where the results are in the target with a narrow spread.

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4.2 Statistical process capability indices

The quality of the design can be defined in different ways, and there are multiple definitions proposed by academia, company R&D and quality departments. The technical quality can be measured from the product, and thus a measured parameter is a quantitative quality parameter. The quality levels for different products, parameters, and functions should be comparable to each other to ease communication between different parties during the development process of the design or product. Process capability indices have been developed for this purpose, and the most widely used is the $C_{pk}$ index in the industry. The PCIs are dimensionless, and quality levels of different parameters are comparable to each other. The most widely used PCI is the $C_{pk}$, which is based on a ratio of the mean value to the specification limits divided by half of the typical process variation. It can be calculated as \[ C_{pk} = \min \left( \frac{USL - \bar{X}}{3\sigma}, \frac{\bar{X} - LSL}{3\sigma} \right), \] (16)

where $USL$ is an upper specification limit and $LSL$ is a lower specification limit, $\bar{X}$ is the mean value of parameter X and $\sigma$ is the standard deviation of parameter X. The $C_{pk}$ is illustrated in Fig. 39, where the design parameter X has not been optimized to the center of the specification limits. Thus, the LSL truncates the probability density function of parameter X and some manufactured parts do not comply with the requirements, yielding a manufacturing loss. The PDF shape of X in the illustration is a normal distribution, but in real-life radio parameters, normally distributed parameters are rare [93]. For an accurate production yield estimation prior to the mass production phase of the product, the PDFs of the main parameters should be known and especially the tail properties of the PDF.

The $C_{pk}$ value has a direct mapping to a quality level of the parameter if the parameter follows a normal distribution. The $C_{pk}$ value can be converted to a expected quality level of the parameter if the parameter follows a normal distribution. A probability of defect can be calculated as \[ p_{defect} = 1 - \Phi(3C_{pk}), \] (17)

where $C_{pk}$ is from (16) and $\Phi$ is a cumulative distribution of a standard normal distribution [94].

Unfortunately, almost all radio parameters are distributed with non-normal distributions, and thus PCI values may be incorrect or misleading about the product.
Fig. 39. Illustration of definition of $C_{pk}$.

quality, if non-normal data is used with a normality-based PCI [93]. The non-normal distribution is the most common distributions in radio engineering based on the author’s over 20 years of experience in industry studying data from R&D, pilot productions, or from mass production. The author has studied the applicability and the usage of the PCIs with different non-normal distributions for radio engineering topics in [55, 93, 95, 96, 97, 98, 99]. Even though the basic $C_{pk}$ definition as such is not the most accurate model of the behavior of complex radio engineering parameters, it is the most accepted and easiest to use. In the literature, a much more complex PCI has been proposed to cope with different characteristics of the statistical distributions into a single metric value, but it is are not widely used due to complex analysis and interpretation of the metric [100]. The non-normality correction of the $C_{pk}$ based on the early work of Clements [101] is the easiest method to improve the accuracy of the quality estimation.

The usage of statistical process control methods, including PCI and DOE in Swedish industry, has been studied in [102]. It was concluded that the large manufacturing companies were using statistical methods in most cases. The primary motivation for these companies was to improve the quality by controlling variability in the production process. Only a couple of percent of the respondents in the study reported using SPC methods systematically with in all relevant processes.

Recent progress of research on the univariate process capability indices with non-normal distributed data has been summarized in [100, 103]. Numerous PCIs have been proposed [103, 104], but the first generation PCIs introduced in the 1980s like $C_r$, $C_p$, $C_{pk}$ are still the most widely used in industry, based on the industry experience of the
Measurement results need to be reliable in order to be used for statistical process control purposes or to be used for statistical or practical inference purposes. A rule of thumb is that the measurement system should be ten times more accurate than the studied parameter, or the measurement system should be allowed to introduce at maximum 10% variability to the measurement results [85]. A statistical measurement system analysis is used to quantify errors, which are introduced to the measurement results due to measurement system variability. A commonly used method to quantify the measurement error is to use a Gage R&R study [85, 92]. The Gage R&R method is based on a variance analysis, and it can determine variations from total the measured variance introduced by parts, operators and measurement repeatability, which can be expressed as [85]

\[
\sigma_T^2 = \sigma_P^2 + \sigma_O^2 + \sigma_R^2,
\]

where \( \sigma_T^2 \) is the total observed variance of the measurement results, \( \sigma_P^2 \) is a variance of the measured parts, \( \sigma_O^2 \) is a variance due to the operator (or the equipment) and \( \sigma_R^2 \) a is a variance due to the repeatability. The recommended setup for a Gage R&R study has two operators which measure ten parts, and are a representative selection of the process variation, with three repetitions in random order [85]. There is another defined MSA called Gage R&R type 1 study, which studies an error introduced by the measurement equipment. In this method, one part is measured by one operator, and the measurement is repeated 50 times [105].

The measurement system capability can be considered to be a special case of the process capability index. The measurement system capability index \( C_g \) for Gage R&R type 1 analysis is defined as in [105]

\[
C_g = \left( \frac{K}{100} \cdot \frac{\text{Tol}}{\sigma_R} \right),
\]

where \( K \) is the tolerance area allowed for measurement uncertainty and \( \sigma_R \) is the standard deviation of the measurement error due to repetition. A typical value for \( K \) is 20 [105]. The Gage R&R method is based on a variance analysis of measurement results from multiple operators as shown in (18). If one operator is measuring one part with repetitions, then measured variance is the variance of measurement error of the gage. The definition of \( C_g \) resembles an alternative definition of \( C_{pk} \) in [94].
Equation 19 is not defined in the case where there is no tolerance defined for variation of the parts, and thus a new version for $C_g$ for the Gage R&R type 1 analysis is proposed as [IX]

$$C_g^* = \frac{\sigma_M^2}{\sigma_P^2}, \quad (20)$$

where $\sigma_M^2$ is the variance due to measurement error and $\sigma_P^2$ is the variance of the measured parts. It is proposed that 10 parts are measured as in a conventional Gage R&R study. In the conventional Gage R&R study, the capability of the measurement system is defined with ratio of variances $(\sigma_O^2 + \sigma_R^2)/\sigma_P^2$, which should be less than 0.1 for a capable measurement system. The same threshold value 0.1 is proposed for the $C_g^*$ index [IX].

4.3 Measurement uncertainties of RF parameters

Most of engineering conclusions are drawn based on measurement results, and the validation and reliability of the measurement results is often overlooked. Errors in measurement results stem from the measurement method, repeatability of measurements due to changes in the measurement system, operators, and variations between the measured units.

A statistical process control based analysis is needed to differentiate the sources of the variations in the measurement results when the variation of the measurement system approaches the magnitude of variation in the DUTs. Control charts for the mean value and the variation of the studied parameters can be used for the measurement result analysis [92, 85]. Nowadays, control charts are used to visualize the measurement results. An analysis of variances (ANOVA) has been used to study contributions of the parameters to the measured variance of the results.

4.3.1 Literature review of measurement uncertainties of RF parameters

Uncertainties in the EMC measurements due to different connector types have been studied, and the measurement uncertainty due to RF for connector N- and SMA-types were found to be 0.005 dB when measurements were done below 8 GHz frequencies [106]. The repeatability of the insertion loss of N- and SMA-type connectors was studied in [107], and 0.004 and 0.006 dB have been reported, respectively. The connector
repeatability of a network analyzer was measured, and a standard deviation of 0.0058 dB at 18 GHz was measured with ten repeated measurements [107].

Passive OTA measurements (antenna measurements) have fewer sources of error compared to conductive measurement (radio transceiver measurements) [108]. The uncertainty of the OTA measurements has been standardized in the Comité International Spécial des Perturbations Radioélectriques (CISPR) 16-1-4 standard, and the standard deviation 0.29 dB is given in the standard for measurements below 1 GHz for measurement distance of 3 meters [109]. The measurements show that the standard deviation can be 1.1 dB for 3 m distance on 200 MHz frequency [109]. The measurement error in an EMC system due to pre-amplifier temperature dependency was analyzed in [110]. The analysis shows that ±0.47 dB variation was measured for the pre-amplifier gain variation at temperatures 15 - 35 °C.

Antenna beam pattern measurement can be taken in an EMC chamber as a LOS measurement, but this method requires a large EMC chamber. An alternative method is to use compact antenna test range (CART) measurements which reduces the size needed to half by reflecting the measurement signal with a reflector. However, the size and shape of the reflector have a significant impact on the measurement accuracy, which was studied in [111]. A typical amplitude ripple of the CART system is 1.0 dBp-p, but already an amplitude ripple 0.5 dBp-p limits the sidelobe level measurement to the -25 dBc level.

Measurement cabling of RF measurements leads to potential error sources for RF measurements. The reproducibility error should not exceed 3.5 dB in the whole EMC measurement system based on the CISPR/A standard. The bending of the cable has a notable effect on the RF performance results. The bending and meandering of the RF measurement cable in EMC RF measurements have been studied in [112]. The meandering of the RF cable was found to be significant to the loss of the cable, which may be >30 dB since meandering generates unwanted resonance notches.

Noise figure of an LNA manufactured using a gallium arsenide (GaAs) process was studied in [113], and a measurement system variation of ±0.1 dB was reported for RF probe measurements. A value of ±0.1 dB was based on 60 samples measured with two repeated measurements, and the repeatability of the measurement was included in the variation.

Digital signal quality is measured with EVM, which has an almost direct relationship with SNR [84]. The EVM measurement is defined by observing the average mean distance of the measurement result on the IQ-data from the ideal digital modulation
constellation point. A calibration of the EVM measurement with two CW signals at different frequencies has been studied in [114]. The advantage of this proposed calibration method is that the used calibration signals can be easily traceable to primary standards.

4.3.2 Measured measurement uncertainties of radio parameters

Radiating OTA tests at mmW frequencies introduce a new location accuracy challenge between the reference antenna and the device under test due to short wavelengths. The fixed positions of the reference antenna and the DUT can overcome the positioning problem. A typical laboratory environment becomes relatively large measured in wavelengths if 5G mmW frequencies are used instead of current sub-6 GHz LTE frequencies. A power level variation in the OTA measurement depends on the sphere over the antenna array and the measurement distance [II]. The variation can be calculated as

$$\Delta P_{\text{max}} = 10\log_{10} \left( \frac{1 + r/R}{1 - r/R} \right)^2,$$

where $r$ is the radius of the minimum sphere enclosing the antenna, and $R$ is a distance between the reference antenna and the DUT [115]. The calculated power variation over the antenna array is presented in Fig. 40. The maximum power level variation is 1.05 dB at 1.8 m or at the boundary of the far-field of the used mmW antenna array [31]. Thus, a 2.0 m measurement distance in OTA measurements was used in the measurement campaign and the maximum expected power variation was 0.84 dB (or ±0.42 dB) [II].

The characterization of the uncertainty of the power level measurement of the OTA measurement was performed with the first radio card prototype version with eight antenna ports [31] and eight RX chains in an RF laboratory environment in [I]. A 50 Ω standard load terminates unmeasured antenna ports during the OTA measurements.

The main factor plot of the measured variance is shown in Fig. 41. The analysis was performed with an ANOVA and a general linear model. The main statistically significant factors are the antenna sub-array and the reference antenna, while the measurement day and the human operator factors are statistically non-significant main effects. The classification was done based on the p-value with the threshold 0.05. The p-value is a significance level in statistical hypothesis testing.
Maximum power variation over antenna array area

![Graph showing power level variation over antenna array area](image)

Fig. 40. Power level variation over the antenna array in an OTA measurement, reprinted by permission Paper [II] ©2018 IEEE.

![Main effects plot for measurement result](image)

Fig. 41. Main effect plot of OTA antenna array measurements, reprinted by permission Paper [II] ©2018 IEEE.
The ANOVA table for the variance analysis is shown in [II]. The reproducibility and the repeatability are pooled together in a total measurement error, contributing 50.4% of the total variance of the measurement results, which is shown in the top left corner of Fig. 42. The standard deviation of the measurement error is 0.445 dB, and 95% confidence interval for measurement accuracy is ±0.89 dB. The measured worst-case measurement confidence interval is double compared with the theoretical maximum expected power variation is 0.84 dB, but a usage of one measurement antenna only improves the measurement accuracy based on the main effect plot in Fig. 41 and the ANOVA tables in [II].

The reflections from surrounding objects and room walls and the floor are potential error sources in antenna OTA measurements which are performed in a laboratory or an office environments. In EMC- and antenna chambers, the inner walls, ceiling and the floor are covered with absorbing material reducing the level of the unwanted reflection signals.
The 5G mmW antennas used in base stations are antenna arrays with a significant number of elements narrowing the antenna radiation beam width to boresight direction. In the PoC system, a 16-antenna element antenna array at both link ends has been used with a measured antenna array gain of 20.0 dBi [31], and the high directivity narrows the main beam width to 7 degrees. Similar antenna array patterns were measured in an EMC-chamber and in the office environment.

At 2m distance, the radiation beam is 12 cm wide, where antenna pattern measurements have been performed. The first Fresnel zone radius for the 5G PoC antenna, where harmful reflections could happen at 28 GHz, is $\pm 7$ cm from the beam center point. If antenna measurements have been done at 1 m height from the RF laboratory floor, then no harmful reflections will happen at a very high level of confidence. The ground reflection has also been tested during antenna pattern measurements with a conductive plate, and the height was varied without any noticeable effect on the OTA measurement results.

The sidelobes of the antenna array may radiate unwanted signals in other directions than the main lobe. However, these signals are attenuated by the antenna array pattern. The first sidelobe level is 15 dB and others are at least 20 dB below the main beam level in the PoC antenna array. The actual reflection directions can be calculated and seen with simple triangle trigonometry. If the laboratory environment is cleared from metal or any other objects for some meters radius from the antenna OTA measurement location, harmful reflections should not happen.

Additionally, if the link level measurements are done in an OTA manner in laboratory or office environments, the transmitted and the received interfering signals outside the boresight direction of the antenna arrays are attenuated by the radiation patterns in the potential reflection directions. As an example, first, the unwanted sidelobe transmitted signal is attenuated by 20 dB with the transmission antenna array pattern. The non-ideal reflection attenuates an additional 10 dB. In the reception, the reception antenna array pattern attenuates again by 20 dB resulting in a 50 dB lower level than the direct LOS signal, which is good enough for antenna pattern testing and high-order modulation signal testing.

Another potential measurement error are unwanted RF signals, which are present during RF measurements. The 5G mmW OTA measurements were done in an RF laboratory where no external interference transmission was in the air at the used 28 GHz frequency band at the time of measurement campaign, which was verified with spectrum analyzer measurements. Additionally, the 5G mmW frequency band had no commercial
operation, since 5G mmW spectrum allocations were not granted for operators at the
time of the PoC radio development. Thus, co-channel external interference during
measurement was minimized.

4.4 Statistical properties of RF parameters

4.4.1 Literature review of the statistical properties of RF parameters

The operational wavelengths of 5G mmW networks are significantly shorter than
currently used systems operating at frequencies below 6 GHz. However, the same
manufacturing processes and manufacturing tolerances are applied with mmW radios.
Thus, the impact of the manufacturing tolerances will be significantly more severe in
mmW radios compared to lower frequency ones. As an example, if an RF component
placement tolerance is 0.2 mm (±0.1 mm), then at 700 MHz frequency this tolerance
 corresponds to 0.00046 wavelengths and at 39 GHz to 0.026 wavelengths in the air.
Actually, the variation happens at printed circuit boards, and a dielectric constant,
i.e. the relative permittivity ($\varepsilon_r$) is 4.0, among currently used PCB materials. Thus,
the corresponding manufacturing tolerance in wavelengths increases from 0.0092 at
700 MHz to 0.052 at 39 GHz. One of the most commonly used PCB materials below
6 GHz is FR-4, which is a glass-reinforced epoxy laminate material. There are multiple
options available for different purposes: low frequency FR-4s such as \[116\] with ($\varepsilon_r$)
4.2-4.9 at 1 MHz, \[117\] with $\varepsilon_r$ 4.25-4.55 at 1 GHz or high performance \[118\], with $\varepsilon_r$
value 3.65 at 10 GHz. There are mmW frequency targeted PCB materials available from
Isola with an $\varepsilon_r$ of 3.0 at 20 GHz \[119\] and Panasonic with an $\varepsilon_r$ of 3.6 at 30 GHz \[120\].

Previous examples highlight, why tolerances need to be analyzed in detail in mmW
radio manufacturing. The same trend will continue at higher frequencies when moving
beyond 5G and 6G systems, which will be taken into use in the 2030 time frame. It
is envisioned that 6G systems will be deployed beyond 100 GHz, and one of the first
candidates are around the 300 GHz frequency range \[121\]. At the 300 GHz frequency,
the studied manufacturing tolerance of 0.2 mm corresponds a 0.4 wavelength on the
PCB board.

The RF parameters are specified in component data sheets with minimum and
maximum values, and those values can be defined in several ways. The minimum and
maximum values can be based on measurement results or on design targets (which is a
typical method for preliminary component specification) or on measurement results with
additional process drift contributions. The latter method is a quality assurance method based on $C_{pk}$ since some additional guard tolerance is added to the measured values, which define the minimum and maximum limits. This method is used to specify the performance limits of power management multi-chip module (MCM) in [122].

RF parameters which are used with an RF amplifier and the most commonly used quality indices in the RF industry $C_p$ and $C_{pk}$ are presented in [123]. A data sheet for a LNA is presented in [124], which shows how the specification limits and quality indices are used for different RF parameters. The datasheet specifies for the $C_{pk}$ index values for the most important LNA parameters, i.e., the IIP3, the gain, and the noise figure based on component measurements (N=450).

If the quality level of the RF parameter is described in the datasheet of the component, then the designer can fine-tune the complete RF design more accurately since the actual component variation, not just the minimum and maximum values, can be modeled.

A high-quality level of the component requires that outlier samples of the production data need to be analyzed. A production data set of a power amplifier module (~100k units) is analyzed in [125], and the analyzed PDFs are highly skewed, but the names of the analyzed RF parameters were not revealed.

RF filter manufacturing has used statistical quality control methods for a long time to optimize the production and product quality levels. Two waveguide bandpass filters operating at 12 GHz and 20 GHz were analyzed in [126] and those were CNC machined from a metal block, and the CNC machine tolerance is $\pm 20$ um ($\pm 10$um for a path and $\pm 10$um for an end-mill cutter). Another example of filter design is a mobile device FBAR duplexer for LTE frequency band 13 in [127]. The band 13 is used in the US for LTE, and it operates in the 700 MHz band (uplink (UL): 777 – 787 MHz and downlink (DL): 746 – 756 MHz). Band 13 is problematic due to the adjacent LTE frequency band 14 (UL: 788 – 798 MHz and DL: 758 – 768 MHz). The frequency response of RF filters drift over their operational temperatures. The frequency response drift needs to be taken into account in RF system level, and an compensated on the component level design. The temperature coefficient of the FBAR duplexer was reported using the process capability index $C_{pk}$ in [127].

Some statistical distributions of RF system parameters are shown in the literature. For example, the probability density function of IIP3 is shown in [128] and statistical analysis of the -1dB OIP model is described in [129].
In conclusion, the statistical properties of RF parameters are not widely shared, since they include information on the production process, which is considered a competitive edge information in the industry.

4.4.2 Probability density function of the noise figure of a phased array receiver

The NF of the phased array receiver of the 5G PoC was calculated by using the RF system calculation spreadsheet in [IV]. The PDF of the NF in the RX array was studied in [VIII]. The illustrated PDF based on an RF system calculations is a skewed distribution, which is estimated based on the minimum, typical and maximum component values used in the RF system calculation, and the resulting PDF is shown in Fig. 43. This kind of RF system analysis is a fast method to estimate the variation of the NF in mass production. However, this analysis can be considered to be a corner analysis, which underestimates the typical values, which are the most common in mass production.

The NF of the RX array of the 5G mmW PoC was simulated using the Monte Carlo-method, which is based on a random sampling of known distribution of parameters to generate random numbers for mathematical experiments, with 500 simulation rounds.

Fig. 43. NF of array receiver based on component to component variations from data sheets with maximum coherence gain, reprinted by permission Paper VIII ©2019 IEEE.
to verify the illustrated PDF in Fig. 43. The component variations have been modeled based on datasheets, and the simulated PDF is shown in Fig. 44. The simulated PDF has a mean of 5.86 dB and the standard deviation of 0.26 dB and the shape of the distribution is slightly skewed with a longtail towards high values similarly as in the illustrated PDF in Fig. 43. The MC-simulated PDF is not as skewed as expected based on the corner case analysis, since the MC-analysis includes more typical values in the simulated population than the corner case-based analysis.

4.4.3 Probability density function of the bit error rate

The mathematical model to convert a variation of the input parameter to the output parameter can be derived as follows: If the input variable \( X \) is mapped with a mapping function \( g(X) \) to the output variable \( Y \), and where \( X \) is the input variable with a known PDF \( f_X(X) \) then the PDF of the output variable \( Y \) can be calculated by mapping the \( f_X(X) \) with an inverse function of \( g(X) \) and scaling it with the derivative of the inverse function [130]. Thus, the PDF of the output variable \( f_Y(Y) \) can be then written as [130]

\[
f_Y(y) = \begin{cases} 
    f_X(g^{-1}(y)) \left| \frac{dg^{-1}(y)}{dy} \right|, & \text{if } y \in Y, \\
    0, & \text{otherwise.}
\end{cases}
\] (22)
where \( g^{-1} \) is the inverse function of \( g(x) \) and \( Y \) is set where \( g^{-1} \) has a continuous derivative.

The NF of the receiver impacts the achievable SNR at the output of the RX, and thus the variation of the NF with fixed gain settings will impact the variation of the SNR at the RX output. Such SNR variation can be observed and measured in pilot or mass production when multiple products are analyzed and measurements are performed with a fixed RF input signal level. The SNR measurement at the output of the RX can be done either with SNR values or with BER values after bit detection. The RX SNR has a direct mapping to the bit error rate when the BER mapping function with the used modulation is known. The shape of the BER curve depends on the used modulation, the coding, and the targeted BER level. The BER curve is a non-linear function, and the PDF of the BER is more skewed than the PDF of RX SNR, which is shown in Fig 45. The mean value \( \mu \) of the SNR is 7.5 dB, and the \( \sigma \) is 0.5 dB for the D-QPSK modulation in Fig 45.

The D-QPSK modulation, without any coding, is a particular case where the BER mapping function is a linear line if the SNR is expressed on a linear scale, and the BER is expressed on a logarithm scale [93]. Thus, if the SNR at the output of the RX for the D-QPSK modulation receiver is normally distributed on dB scale, then the SNR is...
log-normally distributed on a linear scale. Then, the log-normal distributed SNR is linearly mapped to the BER value on the logarithm scale. Typically BER values are expressed on a linear scale, and when the log-normal distributed BER is converted to a linear BER by powering the logarithm PDF, then the PDF of the linear BER follows the extreme value function [93] and [131]. Other modulations have a more non-linear BER curve, and thus the PDF of the BER is more skewed than D-QPSK. However, the skewness of the PDF depends on the target or the mean value of the BER distribution and the lower the BER target is, the more skewed the PDF of the linear BER is. Additionally, the shape of the BER curve, used for SNR mapping to the BER, steepens when the order of the modulation and the coding increases, and this increases the skewness of the PDF of the BER.

A QPSK modulation with $\mu$ of the SNR is 6.7 dB, and the $\sigma$ is 0.5 dB, which was analyzed as a second example of the shape of the PDF of the BER value. The logarithm BER value is shown in Fig. 46 and the linear scale BER is shown in Fig. 47 [99]. The BER values are bit error rates which are calculated based on the measurement results over time. Long measurement times are needed for low BER values if the data rate
Fig. 47. Bit error rate on linear scale, reprinted by permission [99] ©2011 IEEE.

is limited. The measurement time limitation forms a measurement horizon, which limits the accuracy of the BER measurement to detect the shape of the BER curve over multiple devices. The measurement horizon is illustrated in Figs. 46 and 47. It can be seen that the measurement horizon has a different effect on the logarithm and linear BER curves. The measurement horizon may significantly truncate the logarithm BER curve, but for the linear BER, the truncation is not significant due to the PDF shape (extreme value function).

4.5 Statistical properties of antenna parameters

An antenna is an electromechanical device which converts a conducted radio frequency signal to a radiated radio frequency signal and vice versa. Since antennas are manufactured as mechanical components, the same tools and methods of mechanical engineering are applicable to the antennas, as well. Antennas can be manufactured as an individual mechanical component, or they are integrated with other mechanical parts, or they are integrated with electrical circuits. However, in each scenario, some mechanical tooling is needed to produce an antenna. The following methods can be used to manufacture
antennas: cutting, casting, carving, molding, lithography, photochemical etching, or integrated circuit manufacturing, and all these methods include manufacturing tolerances, which will yield variation between products.

In mechanical engineering, the tolerances of different parts construct tolerance chains, and the tolerance chains can be analyzed with statistical methods. Typically multiple parts are needed for a working mechanism, and in assembly or mating of multiple parts into one unit, the tolerances of the parts accumulate.

In order to assess the resulting clearance or interference, tolerance line-up calculations are performed. Arithmetical tolerance calculations are based on extreme cases (worst cases) when all dimensions are at their favorable or unfavorable limit. Statistical tolerance calculations take into account the form of distribution of the dimensions and give the clearance or interference that will not be exceeded with a specified statistical probability [132]. An arithmetical tolerance line-up calculation sums the worst-case tolerances while the statistical tolerance analysis sums the variances of parts together, assuming known statistical distributions. The most widely used statistical distribution is a normal distribution, which perfectly models variations of casted, clipped, or molded mechanical parts based on authors experience.

Antenna manufacturing is a mixture of electrical and mechanical component manufacturing, and both parameters need to be controlled in production as well as in the design of electromechanical part.

### 4.5.1 Literature review of statistical properties of antenna parameters below 6 GHz

MC simulations can be used to simulate the manufacturing effects of different design parameters. There are different methods to plan the experiments and simulations, and these are called DOE methods. One popular method to optimize the number of simulation rounds and experimental configurations is the Taguchi method, which is used in [133] to narrow down the number of MC simulation runs from 135 down to 25 runs in the optimization of a patch antenna design operating at 3.1 GHz frequency. The variation of ±0.5 mm has been used in MC simulations in [133] for the antenna feed point, positioning accuracy, and height of FR4 substrates. Hence, the used variation for the PCB thickness is in the range of 15%, which is larger than a typical commercial PCB manufacturer specified for mass production of an FR4 multilayer board. In another example, the thickness tolerance of a PCB in [134] is expressed to be 10% or ±178 µm.
whichever is the largest. In this thesis, the PCB thickness and tolerance will not be directly simulated. Instead, the tolerance is included as part of other inaccuracies in the statistical analyses.

MC simulations were used to study the main and sidelobe levels in an antenna array in [135]. A tolerance of $\pm 0.5$ dB in the antenna array gain requires a phase accuracy 5 degrees between the antenna elements in a 37 element antenna array [135].

Statistical properties of the first side lobe of a linear antenna array with seven elements operating at 790 - 960 MHz are studied with MC simulations and real base station antenna measurements in [136]. The simulated PDF of the first side lobe follows a log-normal distribution with a longtail towards small values. The MC simulations are done with fixed cable losses and varied phases of the cable at $\pm 4$ degrees with a uniform distribution. The measurements from the implemented antenna array confirms the simulated log-normal distribution of the first sidelobe level [136].

The antenna element positioning accuracy of an antenna array (67 x 37 elements) operating at 2 - 18 GHz with $\pm 60$ degrees steering capability with both E- and H-planes is studied in [137]. The several position errors were MC simulated assuming zero-mean normal distribution with $\sigma = 3.3$ mm and measured position errors $\sigma$ to x-, y- and z-directions were 0.2 mm, 0.03 mm and 0.04 mm, respectively [137].

4.5.2 Literature review of statistical properties of antenna parameters below 40 GHz

The impedance mismatch correction of the antenna has been studied with the Monte Carlo method in [138]. A standard horn antenna at 12 GHz was measured, and based on the measurement results, a statistical model was generated for the impedance mismatch correction error, and it followed a normal distribution with a standard deviation of 0.015 dB [138].

Mechanical tolerances of a reflectarray at 38 GHz were studied in [139], and a standard deviation of 0.3 mm in manufacturing yielded a 1 dB directivity loss of the reflectarray. The study of 25 x 24 elements reflectarray operating at 38 GHz in [139] was extended in [140]. The directivity of the reflectarray is proportional to the variance of the matching distortion. Even though, the standard deviation of the input impedance matching ($S_{11}$) can be up to 25 dB, the variation in the directivity gain and field strength of the reflectarray is significantly smaller, since absolute values of the matching affecting radiated power or to the mismatch loss are minimal [140].
The effect of the manufacturing tolerance to the gain of the rectangular patch, which is enhanced by a substrate-superstrate resonance at 35 GHz, is studied in [141]. It was found that both the separation tolerance and roughness less than ±0.1 mm ensure root mean square (RMS) gain variations less than 0.5 dB. A separation variation of ±0.2 mm variation increases the gain variation up to 2 dB [141].

Reflector antennas are used at millimeter-wave frequencies to enhance the gain (peak gain) of the antenna, and the manufacturing tolerance of the reflector depends on the operational frequency. The manufacturing tolerance should be less than $1/83 \lambda$ with an aperture phase error of 8.7 degrees to guarantee the peak gain within a 0.1 dB accuracy. Thus if the reflector antenna operates at 30 GHz, then the manufacturing tolerance should be less than 120 $\mu$m (0.12 mm) [142].

4.5.3 Literature review of statistical properties of antenna parameters above 40 GHz

The packaging of radio frequency components operating at mmW frequencies is a difficult problem to solve. The highest performance RF components or ICs at mmW frequencies have been unpackaged components which are attached to PCBs with solder or conductive glue. Signal lines from and to the IC have been made with wire bonding. The wire bond itself can act as an antenna, and a manufacturing yield of a loop bond wire antenna operating at 60 GHz has been studied in [143]. A state of art wire bonder with the positioning is used with a location accuracy of 3σ is 25 um [143]. The wire bonding antenna at 60 GHz can be manufactured with > 99.9% yield with wire bonders, and wire-bonding antennas can be used up to 270 GHz in mass production with a high-quality level [143].

A stacked patch antenna implemented in the monolithic microwave integrated circuit (MMIC), which operates at 71 – 86 GHz, is presented in [144]. Antennas are stacked with multiple layers, and the misalignment of layers ±50 um was found to be acceptable. The measurement uncertainty of the antenna gain was analyzed with a root sum square method, and an uncertainty of ±0.59 dB is reported in [144].

Manufacturing and assembly tolerances of large corrugated horn antennas operating at 787 - 950 GHz are studied in [145]. The proposed and studied manufacturing tolerances are from 5 to 20 $\mu$m, depending on the mechanical design parameters, which are analyzed based on MC simulations with commercial methods-of-moments software.
Table 7. Summary of reported statistical parameters of antennas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-6 GHz (FR1)</th>
<th>Below 40 GHz (FR2)</th>
<th>Below 100 GHz (beyond 5G)</th>
<th>THz frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported statistical distributions</td>
<td>Log-normal distribution for 1st array side lobe level</td>
<td>Normal distribution for $S_{11}$ calibration error</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reported manufacturing tolerances</td>
<td>±0.2 mm</td>
<td>±0.2 mm</td>
<td>±0.05 mm</td>
<td>±0.02 - 0.005 mm</td>
</tr>
</tbody>
</table>

Antennas operating at THz frequencies will require accurate manufacturing technology. A microelectromechanical (MEMS) switch horn antenna for 3.25 - 3.55 THz has been implemented with the lithography process in [146] and achieved surface roughness is less than 50 nm (0.00005 mm).

A summary, which collects the main findings of the antenna parameter literature reviews, is shown in Table 7. It can be seen that the requirement for the manufacturing tolerances tightens as the operating frequency increases. It can be seen from the summary that the same tolerances and manufacturing methods are used for sub-6 GHz and mmW radios. This phenomenon was faced by the developed 5G mmW PoC radio, which used the same factories and production lines for PCB manufacturing. Similarly, the SMD component assembly was done with a production line which produces radios operating below 6 GHz.

4.5.4 Probability density function of impedance matching $S_{11}$ due to resonance frequency variation

The most important antenna related parameters from the quality and manufacturability point of view are the location of the main resonance in the frequency, the bandwidth of the resonance, and the impedance matching $S_{11}$ levels at specified frequencies. The resonance frequency of the antenna may change if surrounding elements or objects move close to of the antenna. For example, this can happen with a mobile phone when the user
holds the phone and locates it near to their head for the phone call. The head will load the antenna impedance, and this will shift the main or steepest resonance of the antenna. The steepest antenna resonance is the most sensitive to the frequency shift, as well.

Antenna loading will shift the resonance frequency, but the shape of the antenna resonance remains almost constant, and thus the impedance matching level at the specification limit changes as illustrated in Fig. 48. The X-axis is the frequency on a linear scale, the Y-axis is the $S_{11}$ on the dB scale, the USL is the upper specification limit, and the LSL is the lower specification limit in Fig. 48.

The main resonance variation of the used 5G mmW PoC antenna array [31] was modelled with a PDF $f(x)$ in Fig. 48. The $S_{11}$ shift is illustrated with blue and green curves, which show how the $S_{11}$ changes with the frequency shift. The green curve shows the highest frequency shift $S_{11}$ curve while the blue curve shows the lowest frequency behaviour. Thus, if the lowest frequency specification limit is analyzed, then the PDF of the $S_{11}$ marked with $h(y)$ is a scaled version of the PDF $f(x)$, where the scaling is done with a non-linear function $g(x)$, which is the $S_{11}$ curve. An alternative way to express this is that the $h(x)$ at the LSL frequency is formed by mapping a flipped version of $f(x)$ with the lower part of the function $g(x)$, which is shown in Fig. 48.

An interesting observation is that the PDF of the frequency shift $f(x)$ is flipped at both the lower specification limit (LSL) and the upper specification limit (USL), and the flipped PDF is mapped with the mapping function $g(x)$ to the $S_{11}$ values.
The $S_{11}$ function or the mapping function $g(x)$ was modeled based on EM-simulation results from the 5G PoC antenna element [31]. The upper side of the modeled $S_{11}$ resonance or the upper mapping function $g(x)$ to be used at the USL frequency is shown in Fig. 49. The $S_{11}$ curve of the main antenna resonance was modeled with a 7th order polynomial, which was the lowest order polynomial to model the shape of the curve smoothly for the MC simulation purposes. The EM simulations indicate that the range of notch frequency variation between antenna element resonances is 500 MHz or 1.8% of the center frequency [V].

The advantage of modelling the antenna resonance with a polynomial function is that the number of MC simulations can be significantly increased, when the MC simulations are done with a simple mathematical function instead of computer power heavy EM-simulations. The whole MC-simulation based on the polynomial model can be done faster than one EM-simulation round. The MC simulation based on the polynomial model was performed with 100,000 simulation runs to simulate the resonance shift’s effect on the antenna impedance matching. The normal distribution
was used to model the variation of the primary antenna resonance frequency $f(x)$. A measured range of 500 MHz between the primary resonance peak between antenna measurements was observed, and this range was assumed to represent $\pm 3\sigma$ variation. Thus, the MC simulations were performed with a normal distribution, for which $\mu$ was 27.05 GHz, and the $\sigma$ was 83.33 MHz based on the antenna measurement results.

The simulated PDF of an antenna reflection coefficient $S_{11}$ at the USL frequency (28.0 GHz) is shown in Fig. 50 with a PDF of the conductively measured $S_{11}$ from 64 antenna elements. A good match between MC-simulated and measured antenna PDFs can be seen in Fig. 50. A 3-parameter Weibull distribution was found to be able to model the measured and the simulated PDFs in [V]. The used 3-parameter Weibull distribution is very similar to the reverse log-normal distribution. The reverse log-normal distribution was used to model the measured and simulated PDFs of $S_{11}$ in [IX]. The shape of the PDF of $S_{11}$ in Fig. 50 follows the normal distribution at low values and at high values the PDF is narrowed or truncated due to flattening the mapping function $g(x)$. 

Fig. 50. PDF of the reflection coefficient of one antenna element, reprinted by permission Paper [V] ©2018 IEEE.
4.5.5 Probability density function of impedance matching \( S_{11} \) due to connector location variation

The 5G mmW antenna module was manufactured as a sub-assembly. The antenna PCB and the metal back cover were manufactured separately and then the back cover was glued onto the antenna PCB. The antenna connectors were placed manually on the PCB. The connector was soldered to the PCB and the metal back cover to improve the grounding of the antenna connector.

Antenna connectors’ location accuracies of the were studied in [IX]. The location accuracy of the center of the antenna connector from the design target has been measured in the X-direction (N=172 connectors) and Y-direction (N=142 connectors). The measured average location of the antenna connector from the design target in the X-direction is 0.038 mm and in the Y-direction -0.116 mm. The axes are defined in Fig. 51 and the negative Y-direction is away from the metal back cover. The measured standard deviation in the X-direction (\( \sigma_X \)) is 0.0680 mm (68 \( \mu \)m) and in the Y-direction is (\( \sigma_Y \)) is 0.0655 mm (65 \( \mu \)m). The variations are similar in both directions based on Bonett’s and Levene’s statistical tests of equal variances with a 95% confidence. The correlation between the X- and Y- dislocations were analyzed, and the Pearson’s correlation factor is 0.184 (p-value=0.029), thus, variations can be considered independent of each other. The \( C_g^* \) based on (20) is 4.1% in the X-direction and 6.1% in the Y-direction and, thus the accuracy of the caliber is sufficient for the measurements [IX].
The component placement accuracy of an industrial SMD component pick-and-place machine is in the range of an $\sigma$ value of 20 $\mu$m [147, 148, 149]. It would be advantageous to use a pick-and-place machine for the antenna connector placement. However, the mechanical design of the antenna module may prevent its usage, as for the 5G mmW PoC antenna module.

The effect of the measured dislocation of the antenna connectors was evaluated by mapping the X- and Y- values with the 3-D surfaces, as shown in Figs. 52(a) and 52(b). The mapping of the PDFs in the X- and Y-direction over a 3D-surface is shown in Fig. 52(b). First, the measured X- and Y-values are mapped over the 3-D surface to the $S_{11}$ values and the $S_{11}$ values are further converted to radiated gain values [IX]. The X- and Y-measurement results were converted to the expected radiation gain values. MC-simulations were carried out based on measurement results to simulate the $S_{11}$ distribution behavior with a significantly larger sample size.

### 4.5.6 Probability density function of antenna mismatch loss

The mismatch power loss $S_{21}$ on dB scale can be written as

$$S_{21}(\gamma) = 10\log_{10} \left( 1 - |S_{11}|^2 \right) = 10\log_{10} \left( 1 - \left( 10^{\frac{S_{11}}{10}} \right)^2 \right), \quad (23)$$

where $\bar{S}_{11}$ is $S_{11}$ on a linear scale and $S_{11}$ on a dB scale. Equation (23) applies if the matching network is a passive antenna element and the mismatch power loss reduces the radiated power from the antenna element. The total radiation efficiency $\eta_{\text{total}}$ of an antenna on a linear scale can be written as [69]

$$\eta_{\text{total}} = \eta_{\text{rad}} \left( 1 - |S_{11}|^2 \right), \quad (24)$$

where $\eta_{\text{rad}}$ is the radiation efficiency of the antenna and the second term is the antenna mismatch loss as in (23). The radiated antenna element gain, $G_{\text{rad}}$, from the antenna element on dB scale can be calculated as in [69]

$$G_{\text{rad}} = G_{\text{dir}} - 10\log_{10} (\eta_{\text{total}}) = G_{\text{dir}} - (G_{\text{eff}} + G_{\text{mm}}), \quad (25)$$

where $G_{\text{dir}}$ is the directivity of the antenna element compared to an isotropic radiator, $G_{\text{eff}}$ is the antenna radiation efficiency, and $G_{\text{mm}}$ is the antenna mismatch loss from (24) on dB scale.
Fig. 52. EM-simulated connector location effect on the impedance matching of the antenna connector at 26 GHz (a) in port 1 and (b) in port 2, Paper [IX].
As an example, a log-normal distribution of antenna mismatch $S_{11}$ is mapped to the corresponding mismatch loss, which follows a log-normal distribution, as well, as shown in Fig. 53.

Equation (23) maps the input impedance $S_{11}$ to the PDF of the mismatch loss. As an example, a log-normal distribution of $S_{11}$ is mapped to the corresponding mismatch loss, which follows a log-normal distribution, as well, as shown in Fig. 53. The mapping curve to mismatch loss is non-linear, and it reverses the PDF of the $S_{11}$, and thus the shape of the PDF of the mismatch loss depends on the location of the PDF of $S_{11}$ on the mapping curve. The radiated gain has the same PDF as the mismatch loss since the radiation efficiency, and the antenna gain is constant in (25).

The fundamental statistical properties of the PDFs of $S_{11}$ and the TX power was studied based on the previous simulations and measurements in [IX]. The PDF of antenna impedance to the PDF of mismatch loss or the PDF of the radiated TX power variation to observe the direct relationship was simulated with the MC-method with 100,000 simulation runs. The reverse log-normal distribution was used to model the $S_{11}$, and the $\mu$ and $\sigma$ of the reverse log-normal distribution was varied. As an example, the
PDF of $S_{11}$ with the $\mu$ of -10 dB and $\sigma$ of 5 dB is shown in 54(a), and the corresponding PDF of the mismatch loss is shown in 54(b). It can be seen from the 54(b) that the radiated TX power follows the reverse log-normal distribution which is dependent on the variation of the $S_{11}$ of the antenna. However, the scale of the TX power variation on the dB scale is significantly smaller than the variation of the $S_{11}$ on the dB scale.

The radiated antenna gains of the antenna elements were measured with the OTA method in the RF laboratory environment. The PDF of the OTA measured antenna gains has been shown with a red curve in Fig. 54 and the PDF of the conductively measured $S_{11}$ of antenna elements are shown with a blue curve in Fig. 54. The simulated effect of the misalignment of the antenna connector based on the measurement results of measured dislocations of the connector is shown with a yellow PDF in Fig. 54. The effect of the measurement uncertainty is modeled to the simulated PDF of the antenna dislocation with a purple curve. The purple curve is the expected PDF of the simulated variation with the potential measurement uncertainty based on the Gage R&R study. It can be concluded, that the shapes of the measured PDF of the antenna gain and the expected PDF based on the simulation and the measurement uncertainty have similar shapes and skewness. However, the locations of the OTA measured and simulated PDFs
differ by one dB, which is a typical rule of thumb among the antenna designers on how much the simulated and measured results will deviate.

It can be concluded that a single parameter is not enough to define practical measurement uncertainty, but two or three key non-idealities could be sufficient to model the behaviour of the complex antenna interface.

Variation in the input matching $S_{11}$ was modeled with a reverse log-normal distribution on dB scale in [V]. Monte Carlo-simulations were performed with 100,000 simulation runs with a selected mean and standard deviation value to illustrate the PDF shapes of $S_{11}$ and mismatch loss of the antenna. It can be seen from the MC-simulated results that the shape of the PDF of $S_{11}$ in Fig. 55(a) (reserve log-normal distribution) remains in the mapping of the mismatch loss shown in Fig. 55(b).

The variation of the log-normal distribution depends on both the mean value and the standard deviation of the distribution [131]. The mapping function from $S_{11}$ to the mismatch loss is highly non-linear, and thus, the location or the mean of the input mismatch has a non-linear effect on the mean value and standard deviation of the PDF of the mismatch loss. These effects have been calculated, and the results are shown in Figs. 56(a) and 56(b). The effect of the mean value of $\mu$ of mismatch loss $S_{21}$ is shown in Fig. 56(a) and the standard deviation $\sigma$ of mismatch loss $S_{21}$ is shown in Fig. 56(b).
Fig. 55. The Monte Carlo simulated (a) PDF of input matching $S_{11}$ with a mean value of -10 dB and standard deviation of 5 dB, and (b) the corresponding PDF of the antenna mismatch loss, with a mean of -2.082 dB and standard deviation of 1.159 dB, Paper [IX].
Fig. 56. PDF parameters of the mismatch loss (a) mean value and (b) standard deviation as a function of input matching $S_{11}$, Paper [IX].
5 5G mmW multiradio interoperability

The performance of one radio link is strongly dependent on the radio channel and the RF performance of the radio solution, including variations in components, antennas, and measurement systems. Some of the key aspects of these have been covered in previous chapters. However, the concept of reliability and quality need to be expanded to cover also aspects that are related to the concurrent operation of multiple radios. Virtually all current mobile and base station devices on the market support multiple radio standards, and thus multiradio interoperability is a topic which requires attention during the design phase of the radio solution. Interoperability needs to be studied within the same device or between within the vicinity of each other.

Concurrent operation of different radio systems requires that systems tolerate some interference from other systems. At the same time, radio systems should not generate excess interference which may affect other radio systems. This topic can be analyzed using a quality metric or with a classical RF system interoperability study. Current mobile protocols can operate simultaneously using multiple different RF frequencies, and this has been standardized as a carrier aggregation in LTE and 5G.

Multiradio interoperability is a multi-dimensional optimization aspect, which is not covered or specified in any standard. All currently used radio standards have been defined, so that standard requirements solely concentrate on the frequencies used by the standard with relatively moderate interference scenarios to and from out-of-band blockers. If there are other radios in the same product, then the multiradio interoperability needs to be specified and implemented by the manufacturer of the product. The author has proposed a multiradio interoperability index, which can be used as quality and optimization criteria for multiradio product interference analysis [97].

There is no single solution to guarantee that multiple radios operating at different frequency bands can co-exist without interference. Radio interoperability can be defined with a spectrum consumption model, which is described in [150]. The spectrum model includes the following parameters that define radio interoperability:

- Radiated or conducted transmission power
- Spectrum masks of the transmission and reception signals
- Antenna directivity
- Propagation loss
– Intermodulation masks of the interfering signals
– Transmission and reception timings
– Location and transmission start time

An illustration of interference scenario within the 5G mmW mobile terminal is shown in Fig. 57. There will be multiple radios integrated into the same 5G terminal or a base station, and they will operate simultaneously. The 5G and LTE systems will work at the same time when 5G is operating in NSA mode, when 5G related signaling is done over LTE connection, and when the 5G connection is used for the data transfer.

Two interoperability scenarios have been highlighted in [III]: 1.) 5G mmW system coexisting with an interfering Wi-Fi or LTE Licensed Assisted Access (LAA) system, and 2.) two co-located 5G mmW systems operating at adjacent channels with respect to each other.

The fifth harmonic of the LTE LAA or Wi-Fi transmission will generate harmonic interference falling into 28 GHz band, as shown in Fig. 58. The 5th harmonic interference of the Wi-Fi/LTE LAA transmission is five times wider than the communication transmission. For example, if the LTE signal is 20 MHz wide, the 5th harmonic is 100 MHz, which is in the same range as the 5G mmW signal bandwidth. The Wi-Fi transmission may be up to 160 MHz wide, and the harmonic spurious may be up to

![Fig. 57. Illustration of radio interferences within a 5G mmW terminal.](image)
800 MHz, which is wider than the currently standardized 5G mmW signal bandwidth of 400 MHz [16].

Conducted measurements have been a standard method for verifying the performance of radio transceivers in 2G, 3G, and LTE, and this has been gradually changed towards OTA measurements. The first performance specification which defines most of the radio performance requirements using OTA is the LTE-LAA operating at the 5 GHz frequency band.

![Fig. 58. Wi-Fi/LTE LAA band interference scenarios for the 5G mmW band, reprinted by permission Paper [III] ©2018 IEEE.](image1)

![Fig. 59. Reference planes of interference studies for mmW and WLAN transmitters and receivers within the same radio unit, reprinted by permission Paper [VI] ©2019 IEEE.](image2)
OTA measurements required by 3GPP specifications are performed at the far-field of the antenna array of the radio transceiver, which is illustrated in Fig. 59 with a dashed line. Thus, the effective antenna gain of the antenna array is included in the RF performance. If the antennas are closer than the far-field threshold based on (1), the far-field antenna pattern is not valid because the received signal is not a plane wave.

The far-field threshold distance is 1.8 m for the antenna shown in Fig. 60. If multiple antennas are operating at different frequencies within a single radio unit, the
near-field antenna isolation can be measured between antenna ports using conductive measurements. The conductive measurement plane of the antenna isolation is shown in Fig. 59 (dotted line).

The antenna isolation measurement was done for the worst-case scenario, with the measurement antenna directly pointing towards the mmW antenna array with 40 cm of separation. This emulates the maximum distance within a small cell base station. In mobile devices, antennas are much closer to each other. The measurement setup is shown in Fig. 61, where the measurement antenna is on the left side, and the mmW antenna is on the right side. All unused mmW antenna ports have been terminated with a 50 \( \Omega \) load.

A wideband antenna isolation measurement result up to 40 GHz is shown in Fig. 62. The typical antenna isolation between antennas is from 60 dB to 65 dB, but there are multiple resonances in the isolation. These resonances have been identified with letters, and correspond to the physical dimensions of the mmW antenna array presented in Fig. 60. The calculated resonances of the dimensions in question are summarized in Fig. 63.
The simulated and the measured antenna resonances of the antenna module are shown in Fig. 62. EM-simulations can predict the overall isolation behavior and the resonance frequencies with reasonably good accuracy. The estimation accuracy of the resonance frequencies degrades while the operational frequencies increase due to challenges in accurate EM antenna model creation. Additionally, the EM simulation time extends significantly when the simulation frequency increases since the amount of 3D simulation points increases with used frequency. The absolute RF signal level in the isolation measurement is low, leading to an increase in the noise in the measurements, which can be seen as a ripple in the results, as shown in Fig. 62.

Wideband antenna resonances were simulated using FDTD (Finite-Difference Time-Domain) and FEM (Finite Element Method) methods between two (2 x 2) sub-arrays. The FDTD simulation had a better correlation with measured values and the FDTD results are shown in Fig. 62. A complete array simulation was not feasible due to the simulation time. Thus, lower frequency resonances are not visible in the simulation results.

<table>
<thead>
<tr>
<th>Antenna dimensions</th>
<th>Length in module [mm]</th>
<th>Calculated resonance [GHz]</th>
<th>Definition of dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>89.4</td>
<td>1.937</td>
<td>Whole width antenna module edge to edge</td>
</tr>
<tr>
<td>b</td>
<td>60.5</td>
<td>2.862</td>
<td>Port 6 unit cell mid point to edge of the module port 1 direction</td>
</tr>
<tr>
<td>c</td>
<td>29.5</td>
<td>5.871</td>
<td>Port 6 unit cell mid point to edge of the module port 8 direction</td>
</tr>
<tr>
<td>d</td>
<td>10.7</td>
<td>16.187</td>
<td>Via cavity of unit cell of 4 antenna elements</td>
</tr>
<tr>
<td>e</td>
<td>5.3</td>
<td>32.496</td>
<td>Via cavity of single antenna element</td>
</tr>
<tr>
<td>f</td>
<td>3.8</td>
<td>45.580</td>
<td>Diagonal of antenna element</td>
</tr>
<tr>
<td>g</td>
<td>31.4</td>
<td>5.516 2.758</td>
<td>Outer distance connector to connector (at back side): Half wave length</td>
</tr>
</tbody>
</table>

Fig. 63. Calculated antenna resonances in antenna module of antenna port 6, reprinted by permission [VI] Paper ©2019 IEEE.
Most of the resonances are related to the dimensions of via cavities, but some are related to the measurement port. The antenna isolation measurement was performed from port 6 of the 16-port antenna array. It is good to notice that the physical distance to the edge of the antenna module changes from port to port, affecting the resonance frequency. However, here only port 6 is measured. The longer dimension resonance (b) is clearly visible in the isolation figure, but the shorter one (c) is at a significantly lower level in the spectrum in Fig. 62. The antenna module is symmetrical in both directions and thus similar resonances, as shown in Fig. 62 are visible for port 2 and for the lower row antennas 10 and 14, as well. Potential resonance frequencies of (b) and (c) dimensions are summarized in Fig. 64. It can be seen that the resonances overlap with the 3GPP LTE bands of 2.1 GHz, 2.7 GHz, 3.5 GHz, and the 2.4 and 5.8 GHz WLAN bands.

The diagonal of the antenna element (f) causes a resonance at 40 GHz, which overlaps with another 5G mmW band, n260, which may introduce a new challenge for 5G mmW inter-band carrier aggregation operation.

The blocking of the mmW receiver due to the fundamental transmission of LTE/Wi-Fi is a much more severe problem than the harmonic transmission of the LTE/Wi-Fi on the 5G mmW frequency band. Isolation measurements between antennas operating at LTE/Wi-Fi and 5G mmW frequencies show that the 5G mmW antenna array has multiple low-frequency resonances, which worsen the multiradio interoperability. Different mmW antenna array ports may enable different unwanted low-frequency resonances due to alternating physical dimensions within the antenna array. The unwanted resonances may cover the entire LTE/Wi-Fi frequency bands (from 2 to 5 GHz). The mitigation of these unwanted low-frequency resonances may pose a new design criterion for mmW antenna array design. Isolation improvements may be made by selecting the number of mmW antenna elements appropriately or modifying the antenna array dimensions.

One potential method to improve multiradio interoperability is to add and modify the

<table>
<thead>
<tr>
<th>Potential resonances frequencies [GHz]</th>
<th>Port 5</th>
<th>Port 7</th>
<th>Port 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension b</td>
<td>4.330</td>
<td>2.406</td>
<td>2.112</td>
</tr>
<tr>
<td>Dimension c</td>
<td>3.464</td>
<td>9.623</td>
<td>21.651</td>
</tr>
</tbody>
</table>
ground planes of the antenna modules, so that the ground planes introduce slot structures that signals via OTA and via ground planes are on opposite phases, thus, significantly suppressing the receiver unit interference level, which is proposed by the author in [151].
6 Summary of original papers

In this section, the research work of the reviewed original papers of the thesis is summarized. Each paper discusses one or more of the research questions that were numbered on pages from 23 to 26. The questions are referred to by their corresponding numbers on the following text.

[I] 28GHz Wireless Backhaul Transceiver Characterization and Radio Link Budget

Paper [I] provides answers to Q5 and Q6 of this thesis. In this paper, the RF system engineering aspects of the 5G PoC mmW backhaul radio unit are presented. The system requirements were derived, and the initial performance allocation to the RF blocks based on the requirements is shown in the paper [I]. The initial link range calculation with the main RF block-level parameters was analyzed. The expected RX sensitivity with the 64-QAM is -54.3 dBm, the expected NF of the array RX is 10 dB, and the maximum link range with 64-QAM modulation is 250 meters with a path loss coefficient \( \alpha \) of 2.5. The \( \alpha \) used in the calculations was higher than the free space path loss or line of sight path loss coefficient \( \alpha \) of 2.0 to provide a conservative link range estimation.

The implemented RF architecture and the mechanical construction of the radio unit were presented in Paper [I]. The measured NF of the 1st version of the array receiver with 8 RX chains was 8.0 dB. The measurement results based on the different conductive NF measurement methods varied significantly. The NF of the individual paths of the RX array were measured using a 10 kHz noise level raising method and with two different TX EVM measurements. The first EVM measurement-based method was to compare the fixed (4%) EVM value to the measurement result. The second method fitted an EVM curve to the measured values, based on the noise level rise due to the varied NF of the RX.

It was found that the curve fitting method corresponded the best to the RF system-level calculations. There were gain differences between the RX paths due to manufacturing problems in die bonding, and the effect of this was seen in the coherence gain measurements. The coherence gain measurements were performed using conductive and
OTA measurements.


Paper [II] provides answers to Q3 and Q8 of this thesis. In this paper, the repeatability and reproducibility of the OTA measurements performed in the RF laboratory were studied using the Gage R& R method. This paper was inspired by a process and quality improvement method known as the Six Sigma method, which is based on the following process steps: design, measure, analyze, identify, and control (DMAIC) [28]. An essential process step of the DMAIC process is the M-step, where the repeatability and reproducibility of the measurement system are analyzed. In the paper [II] a 5G mmW antenna array was measured 85 cm above the floor level in a RF laboratory. Each antenna sub-array was measured using an OTA method multiple times by two operators on two consecutive days. It was found that the human operator contributed $\sigma = 0.1$ dB error to the measurements and the repeatability of the measurements contributed $\sigma = 0.44$ dB. The day-to-day variation was $\sigma = 0.1$ dB. The measured variation in the OTA measurements between users was used in Paper [IX] to model the expected variability of the measurements on the top of the calculated antenna gain variation. This kind of modeling matches between the 3D EM simulated antenna element gains and the measured antenna gains.

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

Paper [III] provides answers to Q2 of this thesis. In this paper, the interference scenarios have been presented, that 5G mmW indoor small cell base stations will face in the typical network deployment scenario. 5G mmW base stations will encounter interference from nearby user devices, which are operating at lower frequencies. Two different interoperability scenarios were analyzed in the paper III. The first was a 5G mmW system in co-existence with an interfering Wi-Fi or LTE LAA system operating below 6 GHz frequencies. The second focuses on the case where two 5G mmW systems are co-located and, and serve on adjacent channels. These two are considered to have the most significant impact from the standardization perspective, and they have not been thoroughly analyzed so far for the 5G standards. The lower frequency system, such as
Wi-Fi or LTE, may generate higher-order harmonics, which can collide with 5G mmW frequencies. For example, the 5th harmonic of the LTE LAA or Wi-Fi operating on the 5 GHz frequency band will have harmful transmission harmonics. The linearity of the mmW RX array was measured using a 100 MHz wide, 16-QAM modulated test signal. The IIP3 of the RX array was defined by using the ACP power of the varied RX signal levels at the IF output. The measurement was performed with a modulated communication signal enabling convenient method to measure the linearity of the RX array in R&D and manufacturing. In the traditional IIP3 measurement, two CW signals and RF generators were used. The measured IIP3 with the ACP based measurement method is -5.4 dBm, and the IIP3 of the 1st LNA is -4.0 dBm. The calculated value has an excellent correlation with the value given in the datasheet of the component.

[IV] Design and Measurement of a mmW Mobile Backhaul Transceiver at 28 GHz

Paper [IV] provides answers to Q3 and Q6 of this thesis. An RF system-level design, PCB stack-up of the RF board, and photographs of the RF and the antenna modules are presented in the paper. The RF architecture is a power tree architecture, in which the RX and the TX signals share the same power split and combination structures. The RF PCB is a multi-layer PCB structure, in which a the copper coin-shaped plate is buried inside the board to enhance the heat conduction of the last power amplifier stages. Each RF chain has a bare die phase shifter component, which is directly wire-bonded to the PCB. The first prototype version of the PCB is presented. This was used for the conductive measurements.

The RX coherence gain of the two RX chains was measured, and the result is close to the theoretical 3 dB value. The coherence gain varies between 2.1 and 2.7 dB when the measurement BW was increased from 100 MHz up to 400 MHz. The linearity of the gain control component (i.e., the mmW step attenuator) was verified. The linear attenuation error within the first 10 dB was 1.7 dB. For the 20 dB range, the error was 1.8 dB, and for the full 31 dB dynamic range it was 3.1 dB. The AGC functionality can compensate for this kind of linear attenuation error by using look-up tables (LUTs). The measured RX output signal levels follow mostly linear and monotonic functions except the highest RX input signal levels. At the highest RX input levels, the RX output level was saturated, which was verified by OTA measurements in Papers [VII] and [VIII].
The RX EVM was conductively measured from each RX chain. Differences of over 15 dB in the conductive measured EVM curves were observed. The main reason for the significant EVM performance variation was that some phase components cracked during the wire bonding of the phase shifter die to the PCB.

Even though there were significant differences between RF branches, the shape of the radiated antenna pattern was constant except for the third sidelobes of the antenna array.

The measured conductive RX EVM was 2.0%, which was used as a benchmark for the OTA measurements. The OTA measurements have inherent variability, and a conductive reference measurement was needed. Additionally, the conductively measured EVM curves could be used as a reference shape for the OTA measured EVM curves.

[V] Quality Analysis of Antenna Reflection Coefficient in Massive MIMO Antenna Array Module

Paper [V] answers Q1, Q7, and Q8 of this thesis. In this paper, the quality level of the antenna module was studied based on a statistical analysis of the impedance matching $S_{11}$ of the antenna element. First, the definition of the specification limits were discussed. It was proposed that the same limits should be used in production tests as well as for the design validation testing. The usage of the same specifications would improve communication between different teams during the development process. The frequency variation of the antenna resonance has a non-linear mapping function compared to the variation of the antenna impedance matching.

The antenna impedance matching of the individual antenna element follows a skewed distribution, which has a long-tail towards small values, and the $S_{11}$ best follows the 3-parameter Weibull-distribution. The statistical distribution was validated with simulations and measurements from the implemented antenna modules.

The quality level requirement of the antenna element need to be higher than the quality level of the antenna module if the antenna module is scrapped due to any defective antenna elements. It was found that for the studied antenna module, the design target needs to be one standard deviation unit more stringent than the quality target of the antenna module. The worst value of the $S_{11}$ in the antenna module defines the quality level, and the distribution of the worst-case $S_{11}$ is a highly skewed distribution with a narrow range.
Paper [VI] provides answers to Q2 and Q5 of this thesis. In this paper, the interoperability of the 5G mmW RX with other lower frequency radio systems was studied. The reference interference planes for interoperability were defined in the paper. The reference plane was at the output of the PA module on the TX side. On the RX side, the reference plane came after the impedance matching of the LNA. It was found through simulations and measurements that the 5G mmW antenna module has multiple resonances that are outside of the mmW frequency band for which the antenna has been designed. Various physical dimensions in the antenna array may resonate outside the frequency band, creating a coupling mechanism with interference frequencies that affect the 5G mmW RX. The 5G mmW antenna module may resonate at multiple LTE and Wi-Fi frequencies. Filtering requirements for the 5G mmW RX were derived, and based on these, it can be concluded that the 5G mmW RX may operate simultaneously with LTE and Wi-Fi systems integrated into the same radio unit. The polarization of the interference signal has an effect on the interference signal level, which was observed in the input of the 5G mmW RX. It was found that the interference has maximal coupling with the antenna module when the TX polarization and the physical coupling dimensions were in the same orientation.

Paper [VII] provides answers to Q4 to Q6 of this thesis. This paper shows how to measure the EVM performance of a 5G mmW backhaul link. The measured system EVM is a combination of TX, RX, and RF measurement equipment EVMs. First, the performance of the conducted EVM of the RF measurement equipment was measured. Then, the conductive measurements were replaced by OTA measurements with reference antennas in order quantify the effect of OTA measurement on the EVM measurement. The TX EVM was measured with a reference antenna on the RX side.

Finally, the system EVM performance was measured, and previous contributions were subtracted to find the RX EVM performance. Both TX and the RX signal levels were varied to measure the EVM performance with different signal power levels. This
measurement method enables the virtual extension of the measurement range within the EMC chamber. The EVM performance was measured in a carrier aggregation mode where up to eight 100 MHz wide 5G NR component carriers were measured. It was found that the system EVM performance of four carrier configurations up to 400 MHz was constant. The system EVM performance curve as a function of the RX input power can be divided into different regions from which different RF parameters can be estimated. The RX linearity limits the system EVM performance at the highest RX input power levels. The best RX EVM performance can be measured only in the middle of the signal range.

The noise level of the receiver limits the system EVM performance in the noise-limited region. The NF of the array RX can be derived from the EVM results from the noise-limited range. The NF of the array RX can be found by minimizing the curve fitting error between the combined EVM performances at the thermal noise level region and constant noise figure. At the lowest RX input signal levels, the used modulation will affect the measured shape of the EVM curve. The measured NF of 5.0 dB was better than expected based on the RF system calculations. The usage of the communication signal for the NF measurement enables NF measurement to be performed at significantly higher power levels than in the noise source based NF measurement. High signal power levels enable improvement to the measurement range of the NF.


Paper [VIII] provides answers to Q3 - Q6 of this thesis. In this paper, the OTA EVM measurement presented in the Paper [VII] has been extended to cover EVM measurement with the beam steering. Beam steering is one of the methods in the 5G mmW to improve system coverage. Beam steering was implemented with phase shifters, which were shared by the TX and RX signals at the mmW frequency. Filtering responses of the 5G mmW RX were reported at mmW and IF frequencies. The gain control of the TX and RX signals were studied, and the system EVM was optimized by selecting the TX and the RX gains appropriately. The system EVM measurements were performed in an EMC chamber and outdoors up to a distance of 90 m. A good correlation between the EMC chamber and outdoor measurements were found from short to long distances. A statistical measurement system analysis using the Gage R&R method was performed.
for the EMC chamber measurements. The Gage R&R indicated that the OTA EVM system is capable of performing repeatable measurements.

A new metric for the beamwidth of the communication signal was proposed based on the system EVM measurements. The method compares the measured system EVM result to the threshold EVM value, which is the maximum value for successful communication using the studied modulation. It was found that the beamwidth based on the system EVM can be wider than -3 dB BW but is narrower than the FNBW.

The measured system EVM results estimate a link range of 475 m with 40 dBm of EIRP and 870 m with 45 dBm. It was demonstrated that 256-QAM 5G NR could be used in the mmW band if the TX and the RX contribute an equal share to the system EVM budget.

[IX] Effect of Manufacturing Tolerances on the Antenna Array Performance

Paper [IX] provides answers to Q7 and Q8 of this thesis. In this paper, the simulated and measured performance of the 5G mmW antenna module was reported. It was then shown that the variation of the impedance matching $S_{11}$ of the antenna element can be mapped to the mismatch loss and from that to radiated antenna performance with a non-linear mapping function. The non-linear mapping function modifies the PDF of the $S_{11}$ to a skewed PDF of the mismatch loss and the radiated antenna performance. The location accuracy of the antenna connector affects the $S_{11}$ performance. The locations of the antenna connector in the X- and Y-direction were measured, and the observed PDFs followed a normal distribution. A Gage R&R analysis was performed for the digital caliper, and it was found to be capable of measuring the location of the antenna connector. A new index was proposed for the Gage R&R study for this purpose. The antenna module was assembled with a metal back cover and the antenna PCB. The Gage R&R study was performed with a micrometer caliper to measure the height of the metal cavity. The caliper was capable of the measurement. A gap between the metal cover and the PCB introduced variation to the $S_{11}$, which widens the PDF of the antenna element gain based on the OTA measurements. Simulations were performed to find a background function of the PDF for the $S_{11}$ and the antenna gain. It was found that the $S_{11}$ and the antenna gain followed the log-normal distributions. Finally, the results showed that the selection of the design target of the antenna mismatch and the maximum allowed the variation to have a direct effect on the radiated power. This effect needs to be taken into account during the RF system partitioning and specification phase of the RF components.
for the TX and the RX of a mmW phased array. In small antenna arrays with less than 16 elements, the antenna gain variation due to antenna mismatches may be significant compared to other component variations within the transceiver. The averaging effect will smoothen the antenna array variation significantly in large antenna arrays.

[Thesis] *Thesis chapter text*

In addition to the published papers, this thesis provides additional insights into Q1 and Q3 of this thesis. The development process of the 5G mmW PoC has been studied in this paper. It was proposed that PoCs can be divided into two categories: type 1 for technology demonstrators, and type 2 for system-level demonstrators. A new spiral product development process was proposed and compared to the waterfall development process. The spiral development starts from the circuit design followed by inter-system and tolerance analyses. After these quality analyses, the design can be manufactured. Manufactured prototypes are measured, and the measurement results are compared to the simulated results which are used in the design parameter adjustments for the following prototype rounds. Requirement management is an on-going task that affects all aspects of the spiral development round.

The transmission power level in the OTA measurements was studied in this thesis because all radio devices need to fulfill regulatory requirements before they can be safely operated. The EMF requirement of the developed 5G mmW PoC was analyzed. The safety limit distance for the general population from the radio unit is 50 cm, and for occupational personnel the limit shrinks to 23 cm.
7 Discussion

7.1 Main findings

The development of the system-level 5G mmW PoC which was studied in this thesis was found to follow the product development process of a real industrial product closely. The implemented system-level PoC integrated multiple new technologies into one common platform where all sub-systems need to operate seamlessly together. The integration requires optimized interfaces between different sub-systems. From this perspective, system-level PoC development can be considered standard R&D work. Prototype manufacturing in the same manufacturing facilities where high volume production takes place increases similarities in the final product, since differences can be minimized. The same quality design methods were used to guarantee the success during the production. However, the quality level of the manufacturing for some designs did not meet the expected level.

OTA measurement is the only feasible method to measure 5G mmW array transceivers. The measurement plan was changed to solely OTA measurement after the first RF prototype round because the cabling for conductive measurements was too complicated. OTA measurements with a 5G NR test signal enable multiple tests with the same measurement setup. It was proposed in the thesis that the NF of the RX array can be measured with an OTA measured system EVM by varying the RX signal level. The NF estimation was done by curve fitting the EVM curve due to an increased RX noise level. It was shown in the thesis that the IIP3 of the array RX can be measured with a modulated signal following the same principle as in a traditional IIP3 measurement with two CW signals. The link range of the wireless backhaul system can be estimated based on the system EVM measurements performed in an EMC chamber. Similar EVM measurements were performed in an outdoor environment, and a good correlation between the different EVM measurements was found.

The gage repeatability and reproducibility (Gage R&R) of the OTA signal level at the mmW frequency was studied in the thesis. OTA measurements with, the antenna pattern of the antenna module operating at 28 GHz were performed in an RF laboratory environment, where office furniture was pushed away from the OTA measurement location. It was measured that the measurement error due to repeated measurements, or the standard deviation unit, was 0.45 dB, which is in the same range as the uncertainty
of OTA measurements EMC or antenna chamber used with 4G systems below 6 GHz frequencies. This opens an opportunity to perform some 5G mmW OTA tests in RF laboratories without an expensive OTA measurement chamber. If some R&D OTA tests (at least functionality tests) can be done in RF laboratories without chambers, then the development cost and agility of the 5G mmW development can be improved significantly.

Statistical measurement system analyses are needed for each measurement system to improve the reliability of the measurement results. It was shown in the thesis that the used OTA EVM system as well as used digital rules for mechanical structures were capable of taking the measurements.

The statistical properties of the antenna parameters and their sources of those were studied. It was found that both impedance matching and the mismatch loss of the antenna element follow a reverse log-normal probability density distribution on the dB scale, which can be used to set the design and the manufacturing targets or limits for antenna elements and antenna arrays. The resonance frequency of the antenna element varies due to manufacturing errors leading to antenna input impedance changes, which can be mapped to the antenna mismatch loss with a non-linear mapping function, and the derivation of the function was shown in the thesis.

Multiradio interoperability requires that unwanted signals do not leak from one radio to another conductively or over-the-air. Multiradio interoperability has not been standardized in any specification and this was addressed in the thesis with calculations and verification measurements. The operation of the 5G mmW PoC antenna module outside of the targeted mmW operational band was studied, and several lower frequency resonances were noticed. The unwanted low-frequency resonances were based on multiple physical dimensions within the module. New design criteria for the antenna element and module designs were proposed to avoid these unwanted resonances which would lead to potential multiradio interoperability problems.

The interoperability of the 5G mmW receiver with systems operating in the near vicinity at lower frequency bands was studied when radios were operating on 5G, LTE and Wi-Fi. Two interoperability scenarios were proposed and analyzed: blocking the mmW RX, or harmonic transmission interference on the top of the RX channel. The analysis showed that 5G mmW RX could operate simultaneously with lower frequency transmissions if new interoperability cases are specified, designed, and verified with care.
7.2 Limitations and future work

The future 6G system will challenge the currently used 5G OTA measurement techniques in similar way to how 5G changed the measurement methods compared with the LTE system. The 6G systems will be deployed at significantly higher frequencies than the current 5G system. Thus, the measurement accuracy due to mechanical tolerance requirements will be reduced if similar measurement systems are used as with the 5G. The future OTA measurement systems will require precise alignment and control of the measurement probes, and one potential method is to integrate laser pointers with OTA measurement systems to guarantee the placement accuracy of the OTA measurement probes. The future 6G systems will require new measurement techniques to be developed which can be performed during the regular operation of the device similar to the OTA noise figure measurement presented in this thesis.

The currently used manufacturing methods will limit the physical RF component placement, attachment, and manufacturing yield, and all of these aspects need to be improved for 6G products. The component packaging will be one of the crucial topics to be covered in 6G development, since challenges in 5G mmW development concerning unpackaged components were encountered during the development of the 5G mmW PoC studied in this thesis. Bare die components give the best RF performance, but they are suitable only for prototype purposes, not for mass production of the user equipment.

The availability of accurate mechanical dimension measurements for the thesis was limited to millimeter and micrometer calipers. An optical measurement system with 3D-measurement capabilities will be needed for future radio systems for the components, connectors, or interconnects location measurements. The 6G frequencies may be ten times higher than current 5G mmW system frequencies, and thus at least ten times more accurate dimensional measurement equipment will be needed for physical RF measurements. Such optomechanical measurement systems will be needed on the manufacturing lines of 6G systems, so that calibrations and OTA measurements can be performed quickly, automatically, and accurately during the manufacturing process of 6G devices.

The interoperability scenario of future devices will be significantly challenging since new device generations need to support new frequency bands as well as all previous bands leading the number of combinations of the interoperability scenarios to grow exponentially. Thus, new methods to analyze interference mechanisms due to antenna resonances, transceiver non-idealities, and PCB couplings are needed. Some of these
topics have been covered in the thesis, but significant work will be needed in the future to cover all aspects prior to the mass production of 6G devices.

The number of the produced PoC prototypes in university projects is significantly lower than the total number of prototypes in industrial projects which aims to develop a mass production product. Thus, the accuracy and applicability of the statistical analysis and probability density functions based on a university PoC may be challenged. However, the number of the units of a university PoC is comparable to the first prototype round or first rounds of industrial prototypes. Since significant business decisions in industry are drawn based on relatively small sample sizes, this raises the importance of understanding the fundamental statistical properties of the parameters to support the decision making.

7.3 Applicability of the results

The first 5G mmW networks were launched in 2019, and the first wave of BTS and UE products are now being developed extensively. However, the 5G NR standard is evolving, and there are many open topics still in the standard. OTA measurements have been one of the essential topics for the standardization of the 5G mmW system. The measurement methods presented in the thesis can be applied both to BTS and UE and to the upcoming 5G mmW wireless backhaul products, as well.

OTA system EVM measurement can be applied to both BTS and UE in R&D development and mass production to evaluate the total link performance and individual units. System EVM measurement allows measuring the NF of the 5G mmW RX with a modulated signal, which reduces the amount of expensive measurement equipment.

The derived statistical distributions of antenna parameters can be easily applied to the quality and tolerance analyses of 5G radios during the R&D development and mass production phases. The measurement system analysis based on the Gage R&R method is applicable for RF measurements performed in university-driven PoC development. The same Gage R&R analysis can be conducted in an industrial environment, as well. If the measurement system introduces too much error into the results, then the conclusions will be drawn based on the measurement errors, and this should be taken into account to evaluate the actual measurement results of a prototype or a product in OTA tests.
8 Summary and conclusions

The primary goal of this thesis was to study how to build an early prototype, or a proof-of-concept prototype, for 5G mmW radio and analyze the radio performance with tolerances against anticipated product requirements. The goal was divided into several research questions which all support the primary objective of the thesis. These research questions covered the following topics: the process of building a system-level PoC, multiradio interoperability between 5G mmW and sub-6GHz radio systems, OTA measurements in the RF laboratory and in an office environment, the link range estimation based on short distance OTA measurements, the development of new RF measurement techniques based on EVM measurement, a quality analysis of the antenna array and the statistical distribution analysis of the radio parameters. All the studies in the original papers [I] – [IX], criticized by anonymous reviewers, relate to previously mentioned research questions. They also proposed new insights for related research topics and contained results that have not been presented in the open literature earlier.

The development of the system-level PoC was found to be close to the development of a full-scale product since all main aspects of the product development need to be covered successfully in the PoC development. The requirements management for a system-level PoC follow a similar pattern to those followed in product development as well as the design cycle of the PoC prototype. The same main process steps need to be followed, and a new spiral development cycle was proposed for the PoC development. If the system-level PoC uses the same production technologies as targeted for final product would use, then the system-level PoC will face the same manufacturing, sourcing, and quality issues as the final product.

Some of OTA 5G mmW OTA measurements can be performed in an RF laboratory or office environment without expensive EMC chambers based on the results of the thesis. 5G mmW communication is mainly based on line of sight communication, which can transfer signals successfully in an office environment. The accuracy of the OTA power level measurement at the mmW frequency was found to be $\pm 0.89 \text{ dB}$ within the 95% confidence interval due to variations of the measurement system and different operators using the system.

The system EVM measurement of the prototype radio was found to provide new insights for the development of the 5G mmW system. The same methods can be
applied to the other frequencies, as well. The OTA measured EVM can be used to measure the noise figure of the receiver of the communication signal enabling the RX noise measurement to be performed simultaneously with other RF communication measurements without any additional measurement equipment. Additionally, the OTA EVM measurement can be used to estimate the communication link range as well as the communication beamwidth, which are essential parameters for the network planning of 5G mmW networks. The linearity of the array receiver can be measured with the 5G modulated OTA communication signal without a two-tone test, which is difficult to perform accurately by OTA means at mmW frequencies.

The statistical analysis of the RF parameters is essential from the design quality perspective. Additionally, the shape of the PDF of the radio parameter is needed for the accurate quality level estimation for mass production based on prototype devices. The PDFs of the antenna mismatch and the radiated output power were studied in this thesis. These were found to follow log-normal distributions based on the simulations and the measurement results. Thus, quality estimations should be done with the log-normal distribution rather than the traditional normal distribution during R&D and manufacturing phases of the antenna array transceiver and the antenna module. Antenna elements in the antenna module require more stringent design targets than the whole array module, if the classical manufacturing assumption is used that if any sub-unit fails, then the full unit fails.

The testing of the 5G mmW radio needs to be done with OTA measurements based on the 3GPP standards. Antenna arrays are used in the base station and the mobile station to compensate for the path loss of the mmW frequency. The usage of OTA measurements and antenna arrays introduce new sources of measurement errors, which need to be carefully calibrated. However, the calibration will not overcome the repeatably and reproducibility requirement for the measurements, which need to be studied on case-by-case basis, and even possibly for each measurement range separately.

In conclusion, the development of a system-level 5G mmW radio PoC followed the typical R&D process of product development and faced the same problems with manufacturing, sourcing, and the changing requirements. Thus, the same R&D development attitude and approaches are needed for the university system-level PoC development as for the industrial product. New test methods proposed in the thesis will facilitate device development in the R&D phase and, potentially, overcome some limitations in a number of test cases and enable more parameters to be verified against different requirements.
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