R&S Taiwan Webinar on 5G and beyond – June 2022

5G ADVANCED & PROSPECT OF 3GPP R18 EVOLUTION AND BEYOND

Presenter:
Heinz MELLEIN
Technology Manager
Heinz.Mellein@rohde-schwarz.com

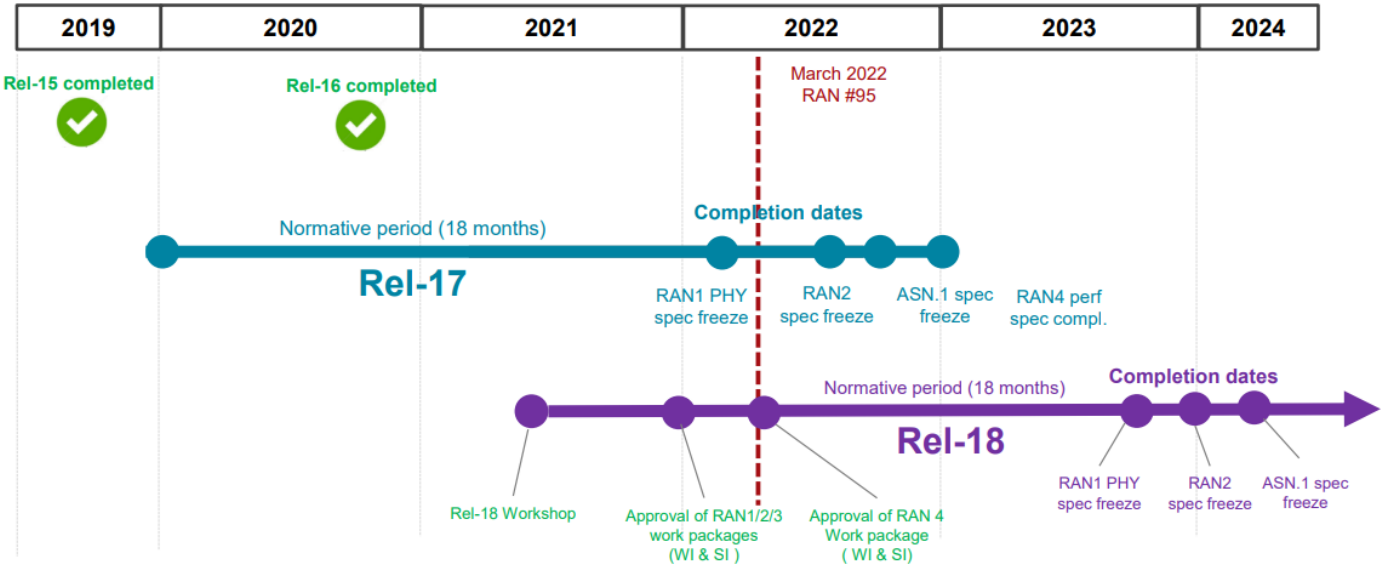
ROHDE&SCHWARZ
Make ideas real

WHAT I AM TALKING ABOUT

- 3GPP roadmap towards Release 18 and beyond
- 3GPP Release 18 features and highlights
- The journey towards „6G“
- „6G“ research highlights and key features

3GPP STANDARDISATION ROADMAP

RAN#95 : 3GPP RELEASE SCHEDULE
MARCH 2022



R18 KICKOFF DISCUSSIONS

Continued NB-IoT support, usage of spectrum chunks, e.g. CA with CC and no SSB sync there, narrowband cell operation

Base station downtime, breathing cell + SON

AI framework for UE, use cases, evaluation, link and positioning prediction, Ref. Signal reduction, beam management

5 MHz UE bandwidth, power saving enhancements, wake-up signals

LTE & 5G broadcast, NR MBS and multicast

New KPI / QoS, application awareness, power consumption coverage, capacity and mobility

SL positioning, high accuracy, RedCap positioning, positioning integrity

SL enh. (unlicensed, power saving, efficiency), SL relay, coexistence LTE-NR V2X

Flexible duplex, eg. DL only deployments, interference management, cross division duplex XDD

L1/L2 inter cell HO, DAPS improvements, FR2 HO

> 4 TX, freq. selective precoding, coverage enh.

CSI reporting + multi-TRP / multi-beam

Indoor 5G + WLAN operation, dual connectivity with > 2 DC

Mobile IAB, smart repeater

Short interruption time, including sidelink into NPN

HAPS + UAV, network slicing NTN, IoT optimizing (no GNSS

V2X in FR2, unlicensed bands, extension up to 114.25 GHz

Reduce measurements, almost zero power RX, energy harvesting

R18 “5G ADVANCED” - EVOLUTION AND REVOLUTION

Mobile Broadband

Extended Verticals

Dynamic Infrastructure

Sensing & Ranging

Wireless Intelligence

Evolution — Revolution

R18 MOBILE BROADBAND

5G NR
| Release 15

5G NR
| Release 16

5G NR
| Release 17

5G NR Advanced
Release 18

> 10 Gbps

Mobile Broadband

"real and urgent demands for improving UL performance needed by many operators/UE for commercialization of networks (i.e.CPE)"

Evolution of MIMO
(DL Multi Panel)

Evolution of MIMO
(UL Multi Panel , up to 8 TX)

FR1-FR2
(up to 52.6 GHz)

Higher Frequency
(FR2-2 up to 71 GHz)

UL coverage

Full Duplex
(on a single carrier)

R18 EXTENDED VERTICALS

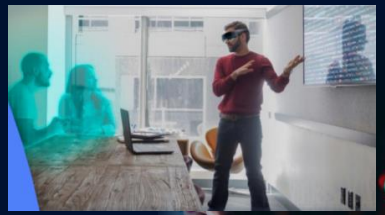
5G NR Advanced
Release 18

5G NR
| Release 17

5G NR
| Release 16

5G NR
| Release 15

Extended Verticals



URLLC/IIOT
(Ultra Reliable, Low latency)

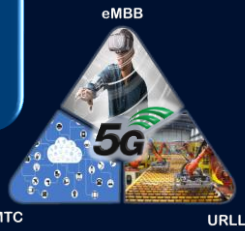
Extended Reality

Reduced Capabilities

eRedCap for Smart Grid/Energy Harvesting

Drones/Uncrewed aerial vehicles

Broacast for critical situations & public safety



R18 INFRASTRUCTURE

5G NR
| Release 15

5G NR
| Release 16

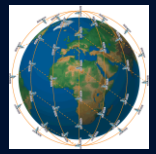
5G NR
| Release 17

5G NR Advanced
Release 18

Smart Infrastructure

RIS - Reconfigurable Intelligent Surface

Wireless Access Backhaul (IAB)



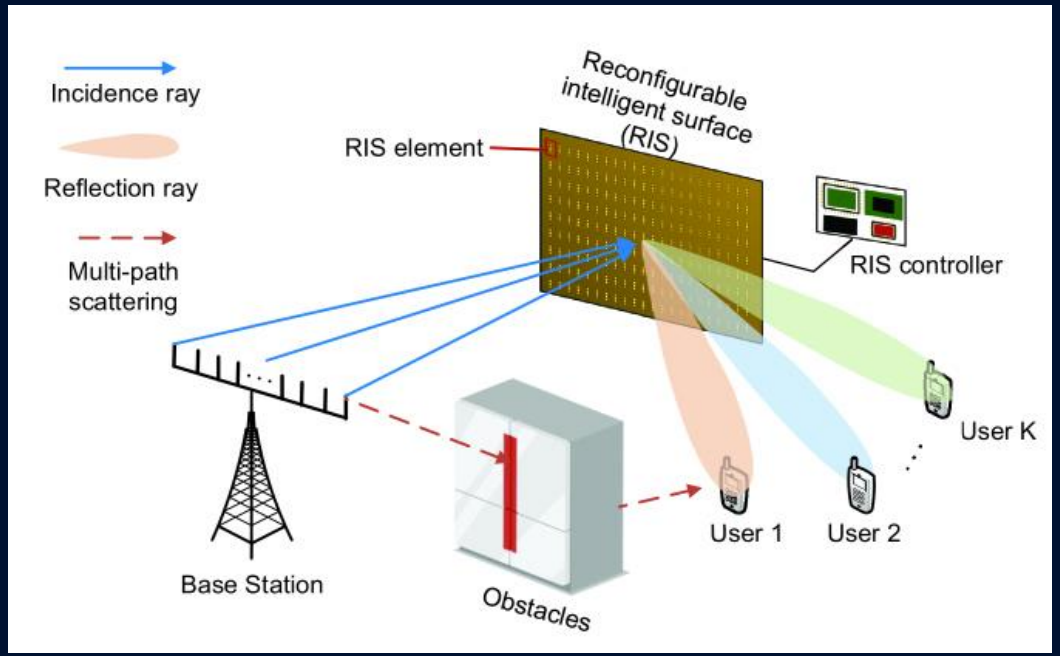
Non Terrestrial / Satellite

UE Power Saving

Network Energy Saving

R18 SMART REPEATING

► Study item on NETWORK-CONTROLLED REPEATERS (NCR)



R18 SENSING & RANGING

5G NR Advanced
Release 18

5G NR
| Release 17

5G NR
| Release 16

5G NR
| Release 15

Sensing & Ranging

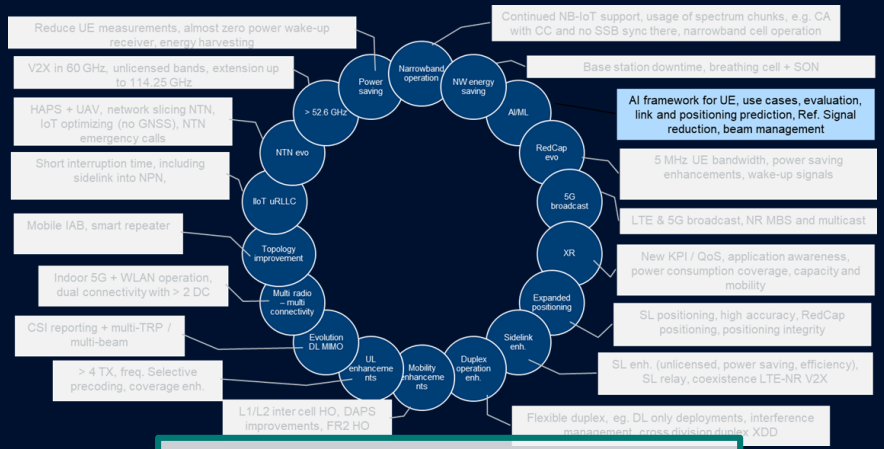
Sidelink
V2X/Automotive

Sidelink/Relay for
IIOT/Personal Network
FR2/CA/NR-U

Sidelink
for sensing and ranging
(Positioning)

R18 MACHINE LEARNING FOR WIRELESS

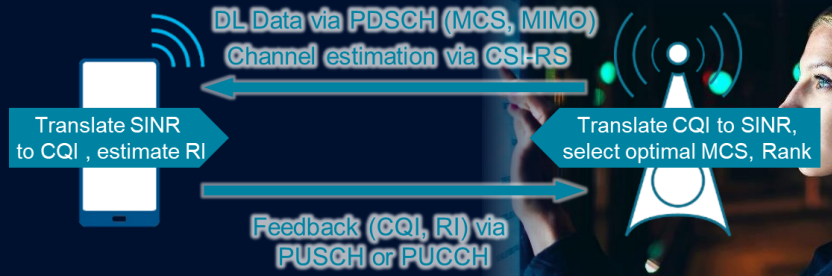
FIRST STUDY ITEMS FOR 5G-ADVANCED



Initial set of used cases to study:

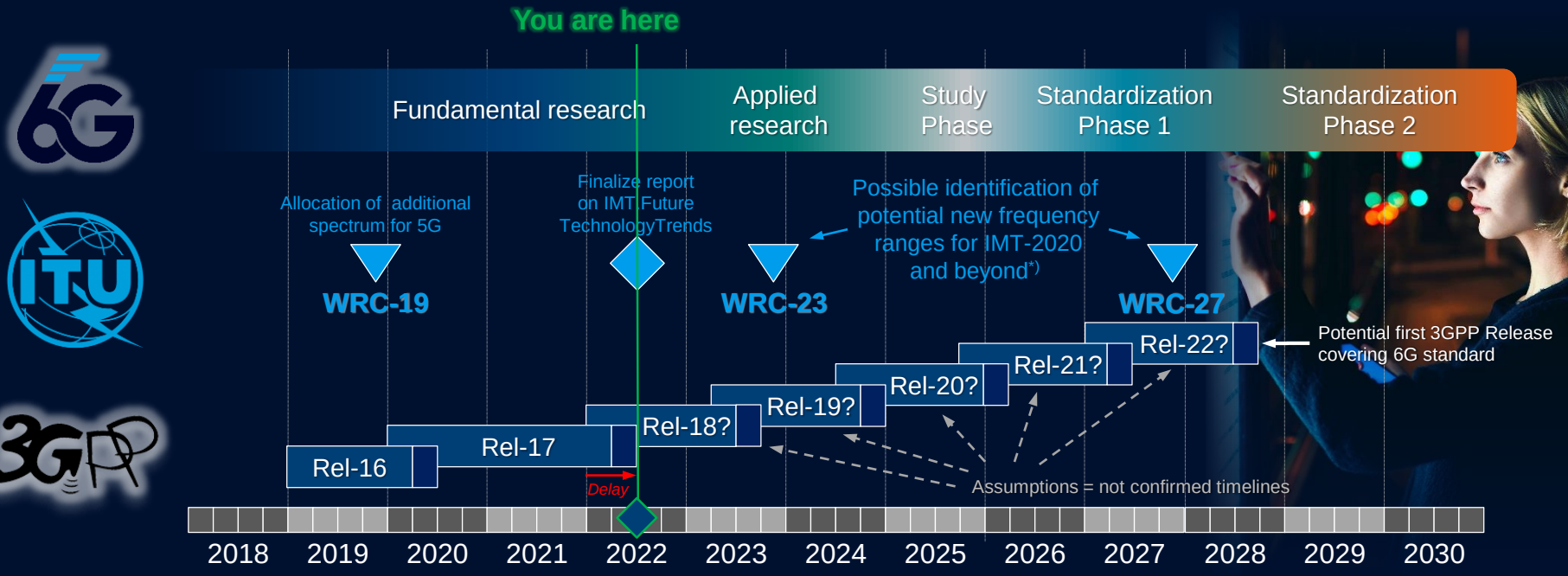
- CSI-feedback enhancement
- Beam management
- Position accuracy enhancement

► Potential ML use case: link adaptation



- Benefit of an AI/ML-based approach is to learn the relationship between CSI-related values and the ACK/NACK flows, incl. the relationship with BLER
- gNB scheduler selects MSC, RI based on ML-model output

STANDARDISATION AND REGULATION ROADMAP



*) *IMT-2020 systems are usually called 5G. The ITU has already started a new report to prepare the work on IMT-2020 and beyond that is likely to become 6G*

DID YOU REALIZE, THAT …

META AND MICROSOFT JOIN HANDS FOR METAVERSE! ANOTHER BIG TECH DOMINANCE?

AUGMENTED/VIRTUAL REALITY LATEST NEWS
by arti / June 24, 2022

- **„Odd numbered G‘s“ where almost exclusively for business, „even numbered G‘s“ for consumers**
  - 1G – Mobile telephone connections for business people
  - 2G – Full commercialisation of mobile telephony
  - 3G – Business oriented, internet based applications like email clients for business people
  - 4G – Consumer oriented, internet based applications for almost anything
  - 5G – Focus on verticals, like Automotive, IIoT, corporate networks
  - **6G – Holographic communication, XR („Metaverse“) applications for everyone, digital twin ???**

- **And from odd to even „G“s, there was always a change on the PHY**
  - 1G to 2G – Analogue to Digital
  - 3G to 4G – CDMA/TDMA/FDMA to OFDMA
  - **5G to 6G – Single RAT (OFDMA) to multi-RAT (SDR, AI based RAT selection) ???**

RESEARCH AREAS FROM A T&M PERSPECTIVE

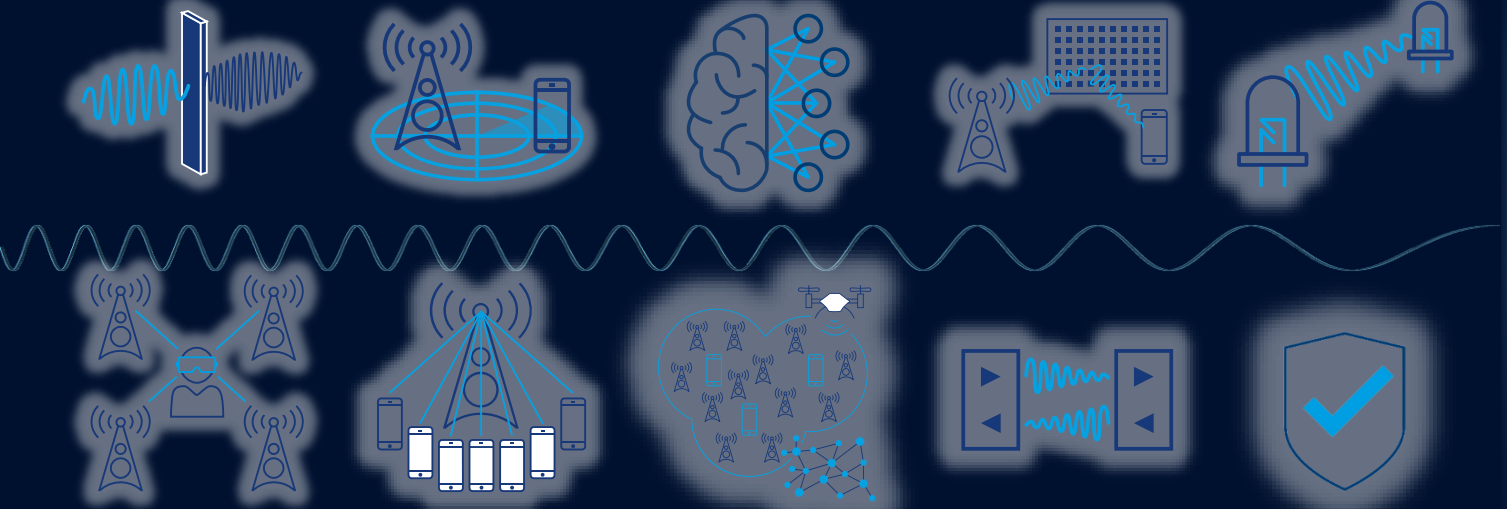
THz communication

Joint communication & sensing

Artificial Intelligence and Machine Learning

Reconfigurable Intelligent Surfaces

Photonics, Visible Light Communication



Multiple access, new waveforms, channel coding

Ultra-massive MIMO

New network topologies, distributed computing

Full-duplex communication

Security & Trustworthiness

A high-level overview on all these research areas is provided in one of our #THINKSIX video. Don't miss it!

SELECTION OF R&S 6G ENGAGEMENTS WITH ACADEMIA & INDUSTRY

6G RESEARCH AREAS

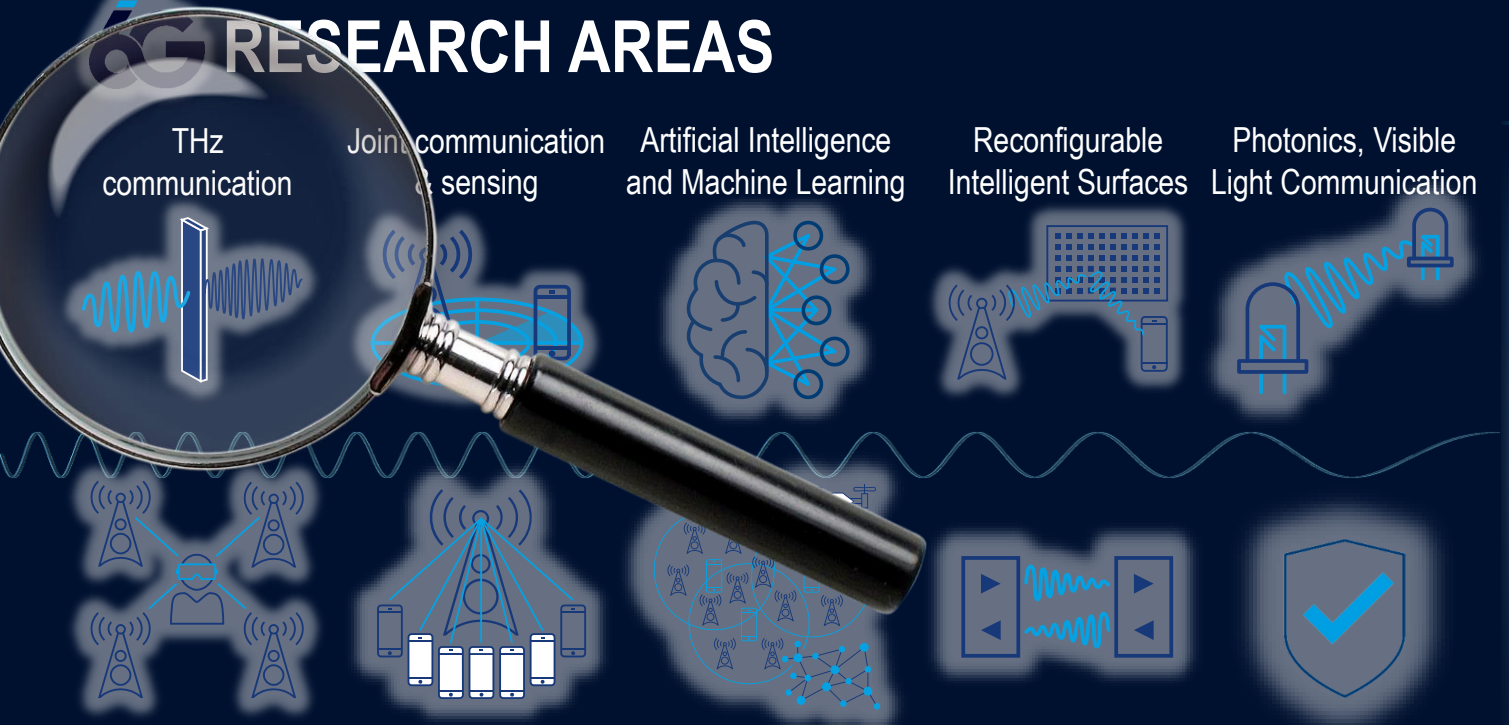
THz communication

Joint communication & sensing

Artificial Intelligence and Machine Learning

Reconfigurable Intelligent Surfaces

Photonics, Visible Light Communication



Multiple access, new waveforms, channel coding

Ultra-massive MIMO

New network topologies, distributed computing

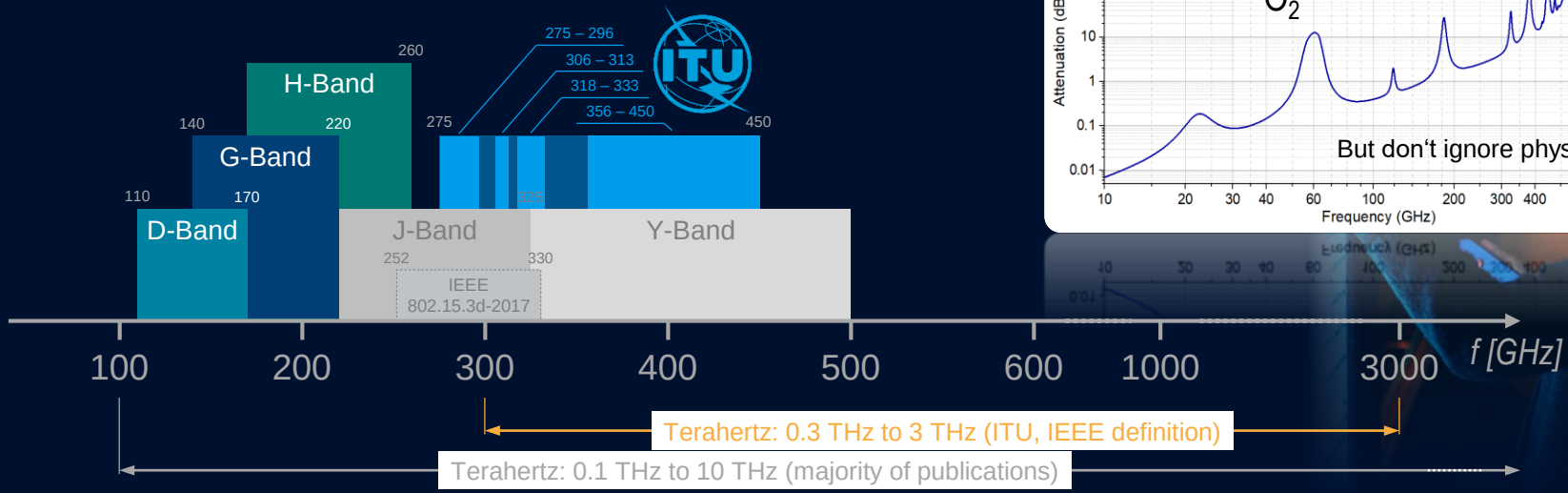
Full-duplex communication

Security & Trustworthiness

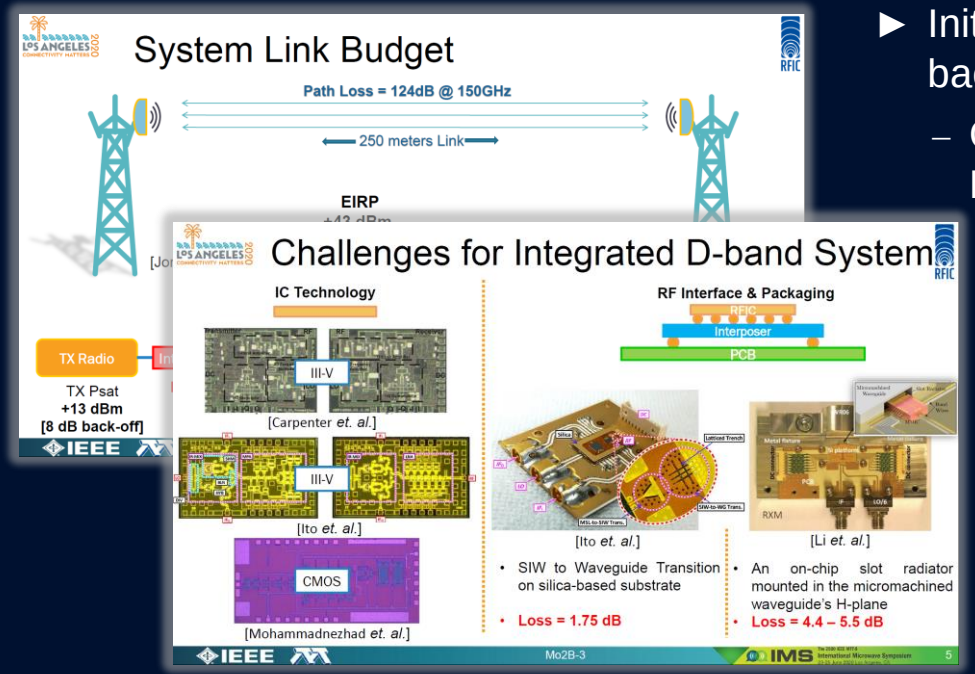
A high-level overview on all these research areas is provided in one of our #THINKSIX video. Don't miss it!

6G SPECTRUM OUTLOOK

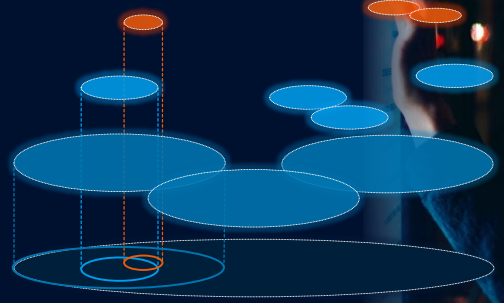
- Let's be clear, a future 6G standard will also work below 100 GHz, below sub-6 and 1 GHz!
- (sub-)THz offers a promising extension of the spectrum



SUB-THZ FOR WIRELESS BACKHAULING AND CELLULAR?



- Initial use case for D-Band is wireless backhaul and fronthaul applications
  - Cellular: ultra-hot spots in combination with FR2?



Ultra-hot spots
> 100 GHz

Hot spot layer
< 48 GHz

Capacity layer
< 6 GHz

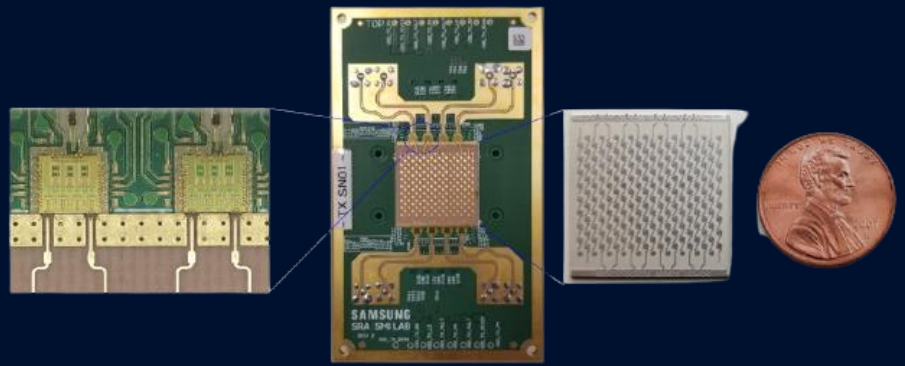
Coverage layer
< 1 GHz

Source: Nokia Bell Labs; https://ieeetv.ieee.org/shahriar-shahramian-rfic-industry-showcase-ims-2020 (Aug 2020)

OUR CUSTOMERS ARE ACTIVELY WORKING ON D-BAND

Samsung Electronics and University of California Santa Barbara Demonstrate 6G Terahertz Wireless Communication Prototype

Korea on June 16, 2021 Audio Share

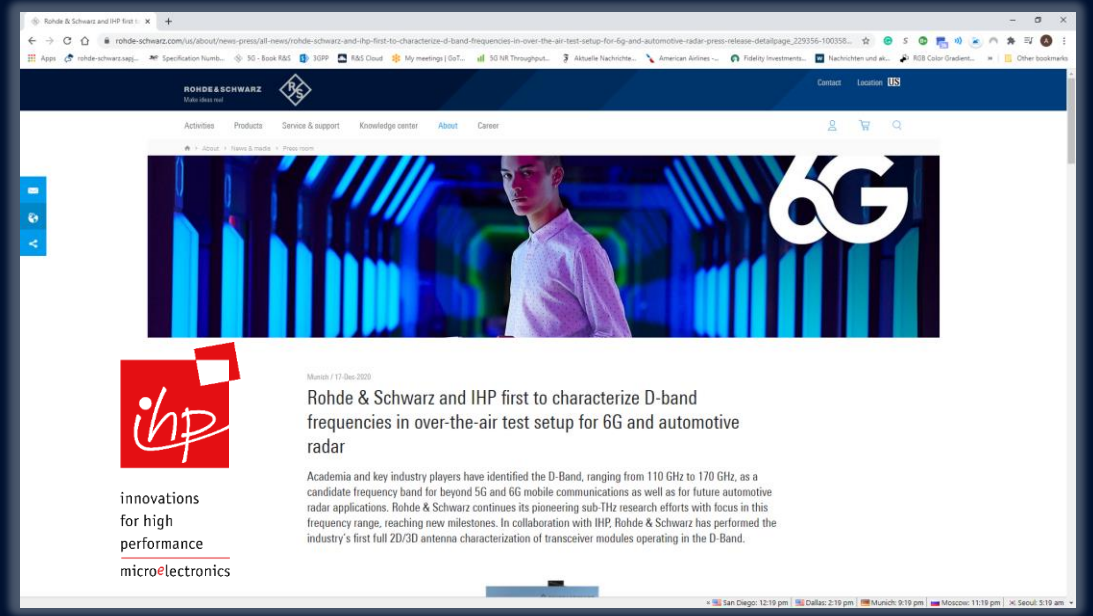


- CMOS-based D-Band (110 to 170 GHz) RFIC with 128 antenna array elements
- 2 GHz BW, MIMO 2x2, 16QAM lead to 6.2 Gbps (E2E) over 15 m distance

https://news.samsung.com/global/samsung-electronics-and-university-of-california-santa-barbara-demonstrate-6g-terahertz-wireless-communication-prototype [June 2021]

INDUSTRY'S FIRST OVER-THE-AIR CHARACTERIZATION OF A D-BAND (110 TO 170 GHZ) TRANSCEIVER MODULE

- … so do we



R&S®ATS1000
Antenna Test System

https://www.rohde-schwarz.com/us/about/news-press/all-news/rohde-schwarz-and-ihp-first-to-characterize-d-band-frequencies-in-over-the-air-test-setup-for-6g-and-automotive-radar-press-release-detailpage_229356-1003584.html (Dec-17, 2020)

6G RESEARCH AREAS

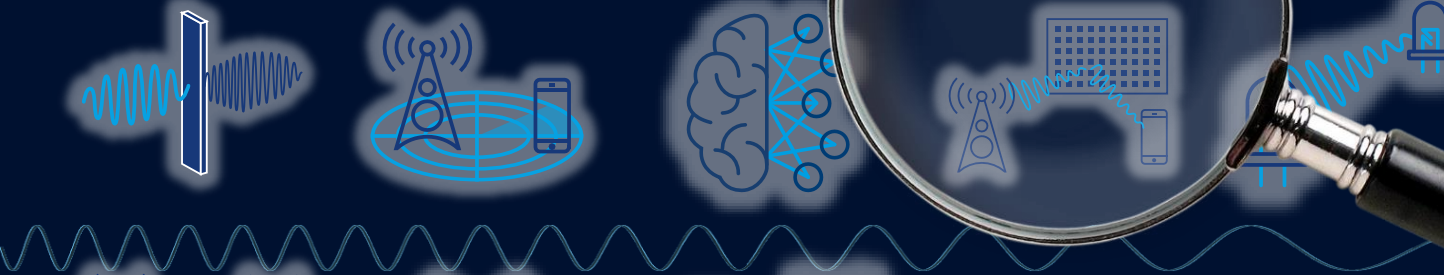
THz communication

Joint communication & sensing

Artificial Intelligence and Machine Learning

Reconfigurable Intelligent Surfaces

Photonics, Visible Light Communication



Multiple access, new waveforms, channel coding

Ultra-massive MIMO

New network topologies, distributed computing

Full-duplex communication

Security & Trustworthiness

A high-level overview on all these research areas is provided in one of our #THINKSIX video. Don't miss it!

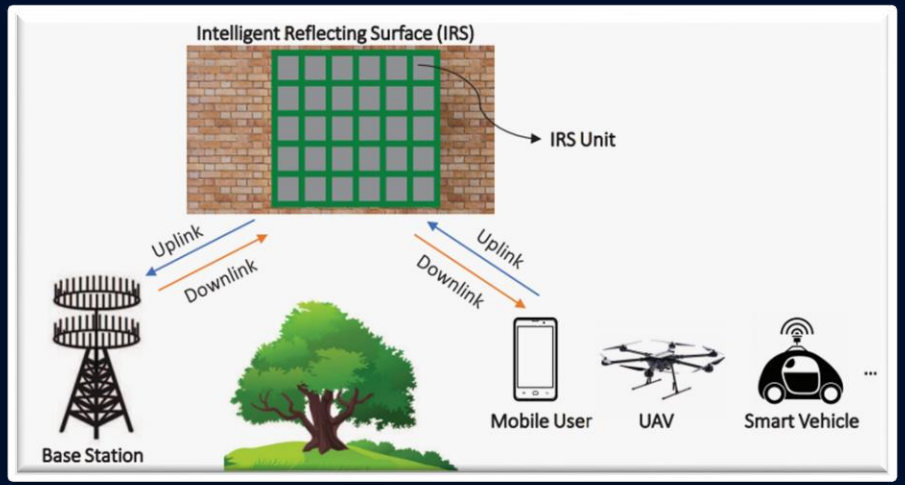
THE RADIO CHANNEL – JUST A MATTER OF FACT ?

$$r(t) = h(t)s(t) + n(t)$$

- Classical approach to maximise reception quality:
  - **Adapt $s(t)$ transmission scheme to target channel $h(t)$**, e.g. CP-OFDM for multipath channel, carrier frequency and bandwidth, pre-coding/equalization, modulation and coding schemes etc.
  - Estimate and equalize the channel $h(t)$.
- **Disruptive approach offered by Reconfigurable Intelligent Surfaces (RIS)**
  - **Adaptation of channel $h(t)$** in order to maximise reception quality and channel capacity.

RECONFIGURABLE INTELLIGENT SURFACES (RIS)
INTELLIGENT REFLECTING SURFACES (IRS)

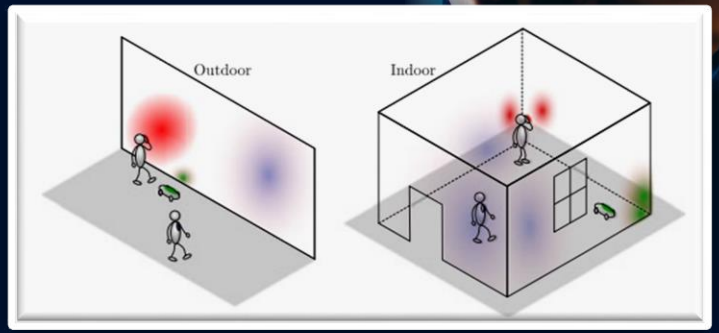
- **RIS (or IRS) tune wireless environments to increase spectrum and energy efficiencies**
  - **Reconfigurable reflect arrays**
  - **Liquid crystal meta-surfaces**
  - **Programmable meta-materials**



RIS-aided wireless communications

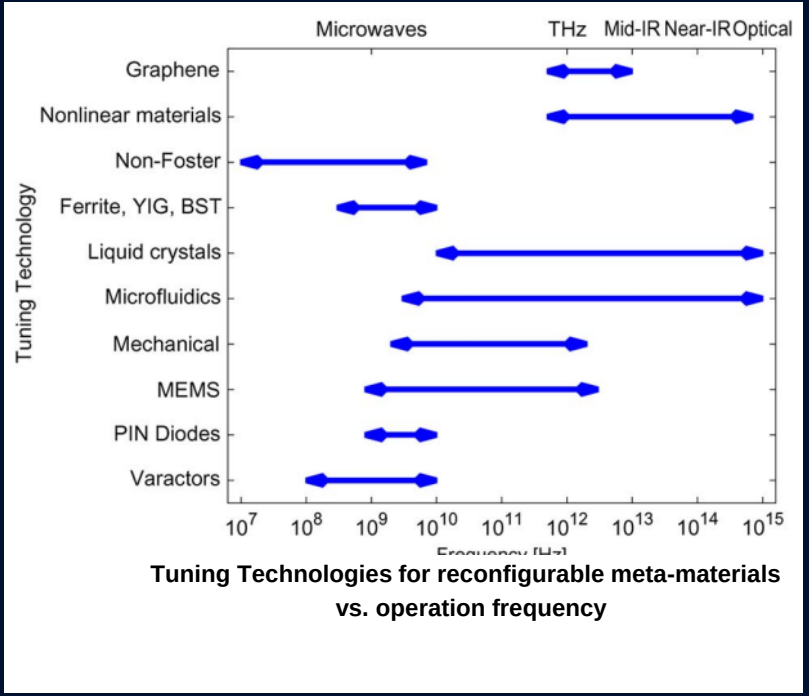
"man-made structures become more and more electronically active, with integrated electronics and wireless communication making the entire environment intelligent"

Source: IEEE TRANSACTIONS ON SIGNAL PROCESSING, VOL. 66, NO. 10, MAY 15, 2018

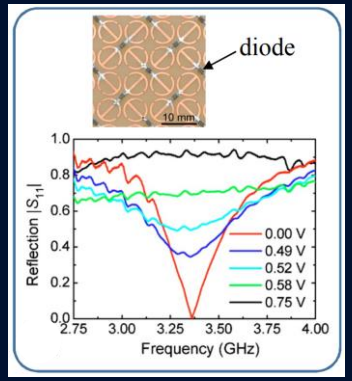


RIS-based wireless communications

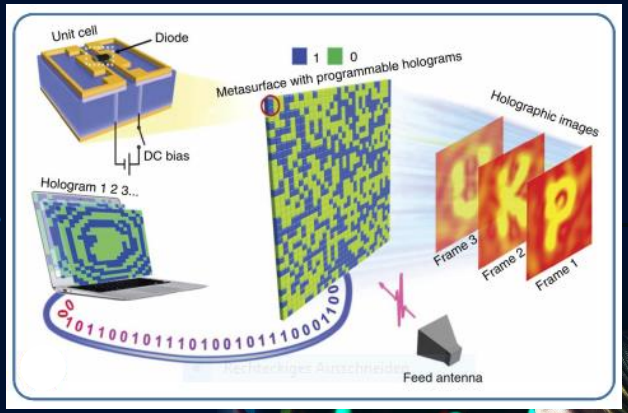
META MATERIALS



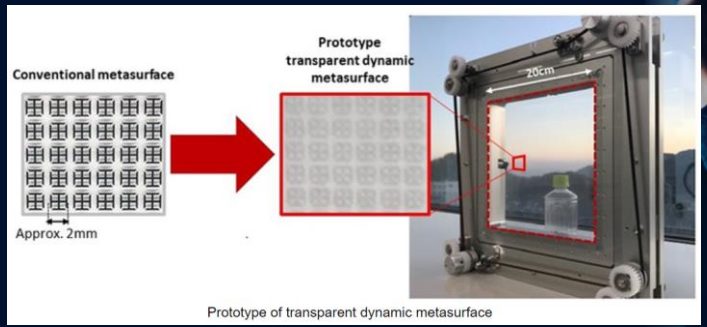
Tuning Technologies for reconfigurable meta-materials vs. operation frequency



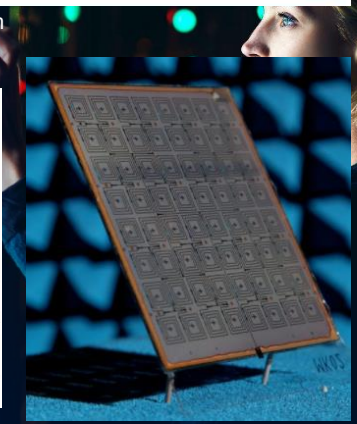
Reflection control with varactors



Dynamic hologram creation



Prototype of transparent dynamic metasurface

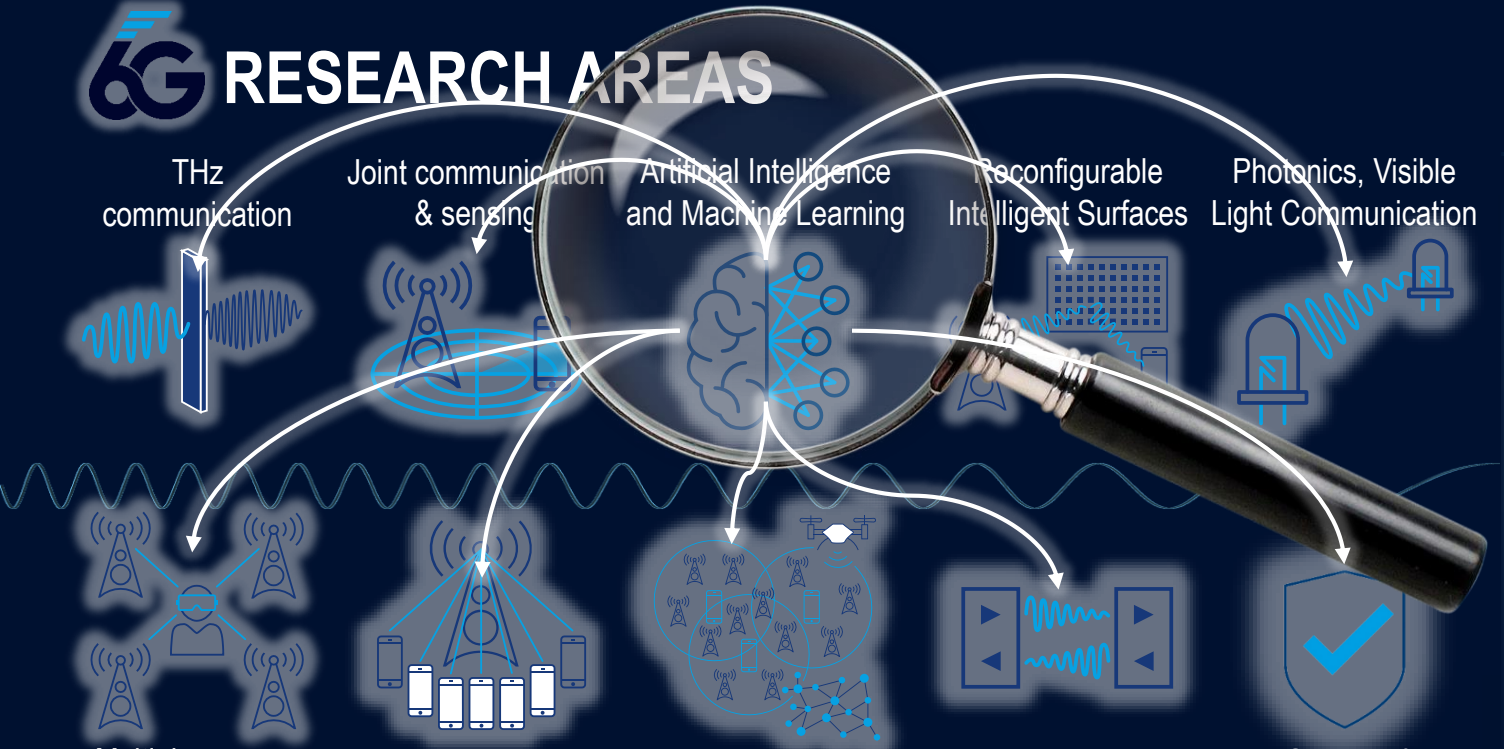


LC based phased-array antenna

- VARACTORs (variable capacitors, e.g. used in VCOs or frequency multipliers)
- microelectromechanical systems (MEMS)

Source:Oliveri et al.: Reconfigurable Electromagnetics Through MetamaterialsVA Review, Proceedings of the IEEE | Vol. 103, No. 7, July 2015

6G RESEARCH AREAS



A high-level overview on all these research areas is provided in one of our #THINKSIX video. Don't miss it!

WHAT IS ARTIFICIAL INTELLIGENCE ?

OECD

Article 3 (1) AIA

*"a software that is developed with one or more of the techniques and approaches **listed in Annex I** and can, for a **given set of human-defined objectives**, **generate** outputs such as content, predictions, recommendations, or decisions influencing the environments they interact with"*

+

Annex I

3 main paradigms of 'intelligence'

- **Learning** (ML approaches)
- **Reasoning** (logic – and knowledge based approaches)
- **Modelling** (statistical approaches)

Regulators getting interested in AI:

EUROPEAN COMMISSION

Brussels, 21.4.2021
COM(2021) 206 final

2021/0106 (COD)

Proposal for a

REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

LAYING DOWN HARMONISED RULES ON ARTIFICIAL INTELLIGENCE (ARTIFICIAL INTELLIGENCE ACT) AND AMENDING CERTAIN UNION LEGISLATIVE ACTS

Source: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12527-Artificial-intelligence-ethical-and-legal-requirements_en

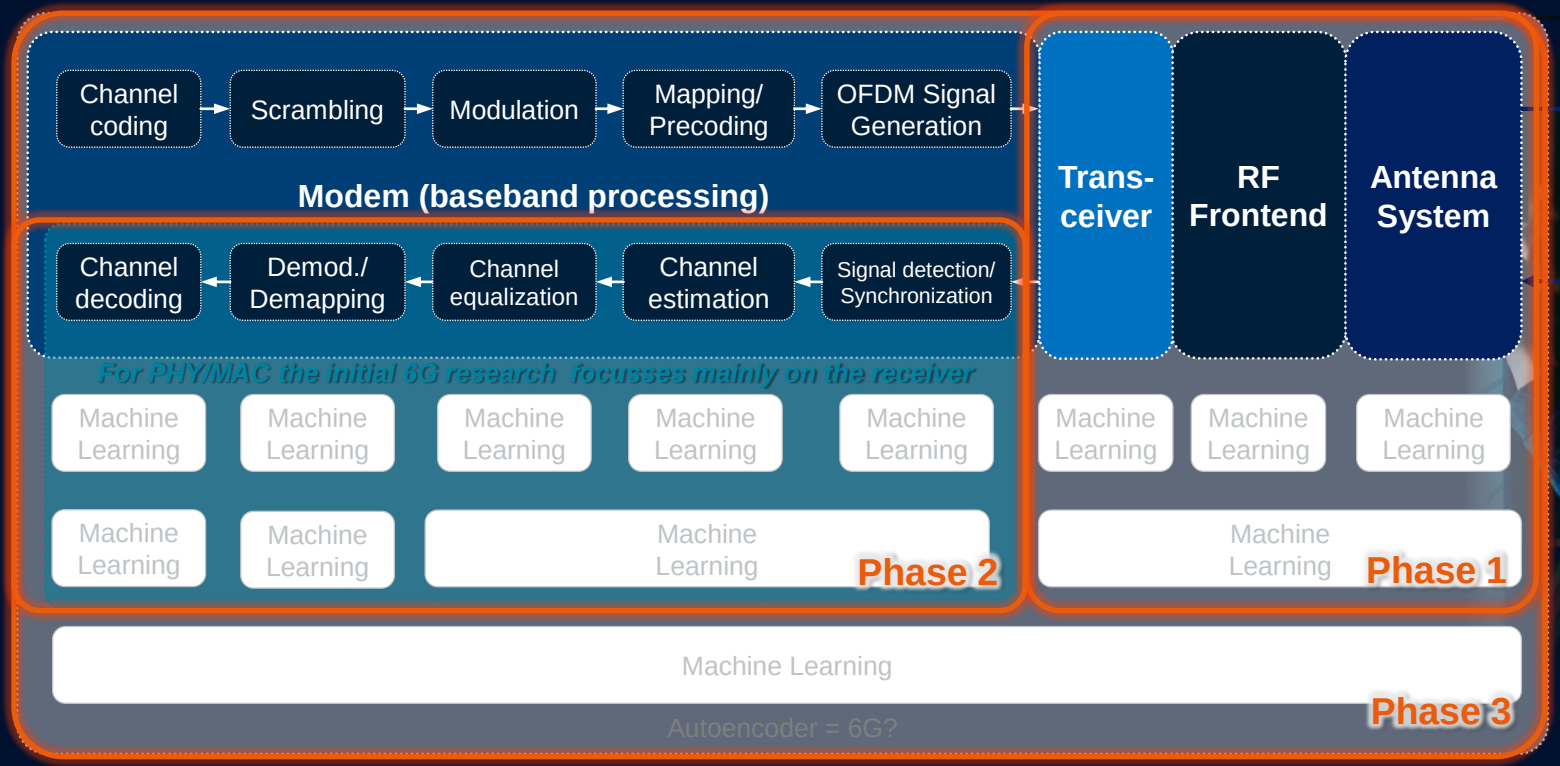
PARADIGMS OF INTELLIGENCE

a) ML approaches, including supervised, unsupervised and reinforcement learning, using a wide variety of methods including deep Learning

b) Logic- and knowledge-based approaches, including knowledge representation, inductive programming, knowledge bases, inference and deductive engines, reasoning and expert systems

c) Statistical approaches, Bayesian estimation, search and optimization methods.

HOW TO APPLY MACHINE LEARNING FOR 6G PHY?
WE THINK THREE MIGHT BE THREE PHASES



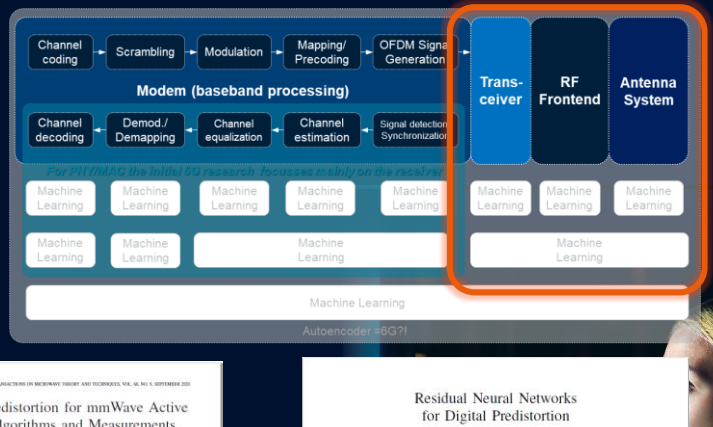
ML applied to individual processing blocks

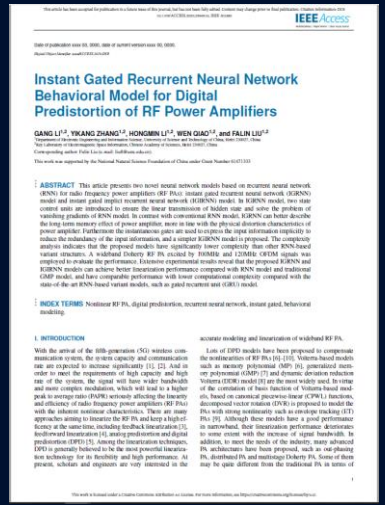
ML replaces multiple processing blocks

ML used to jointly optimize TX, RX and baseband processing; ML designs part of 6G PHY/MAC itself

PHASE 1 IS RF FOCUSED AND NOT NECESSARILY 6G RELATED!

- Optimization of RF Frontend, modelling the non-linearities, analog and digital impairments seems to be an ‘easy’ entry point for applied machine learning in wireless communication.




Instant Gated Recurrent Neural Network Behavioral Model for Digital Predistortion of RF Power Amplifiers

GANG LI[1,2], YIKANG ZHANG[1,2], HONGMIN LI[1,2], WEN QIAO[1,2], and FALIN LIU[1,2]

[ABSTRACT] This article presents two novel neural network models based on recurrent neural network (RNN) for radio frequency power amplifiers (RF PAs): instant gated recurrent neural network (IGRNN) model and instant gated simplict recurrent neural network (IGRNN-SIM). In IGRNN model, two state control units are introduced to ensure the linear transmission of hidden state and solve the problem of vanishing gradients of RNN model. In contrast with conventional RNN model, IGRNN can better describe the long term memory effect of power amplifier, more in line with the physical distortion characteristics of power amplifier. Furthermore the instantaneous gates are used to express the input information implicitly to reduce the redundancy of the input information, and a simpler IGRNN model is proposed. The complexity analysis indicates that the proposed models have significantly lower complexity than other RNN-based variant structures. A wideband Doherty RF PA excited by 100MHz and 120MHz OFDM signals was employed to evaluate the performance. Extensive experimental results reveal that the proposed IGRNN and IGRNN models can achieve better linearization performance compared with RNN model and traditional GMP model, and have comparable performance with lower computational complexity compared with the state-of-the art RNN-based variant models, such as gated recurrent unit (GRU) model.

[INDEX TERMS] Nonlinear RF PA, digital predistortion, recurrent neural network, instant gated, behavioral modeling.

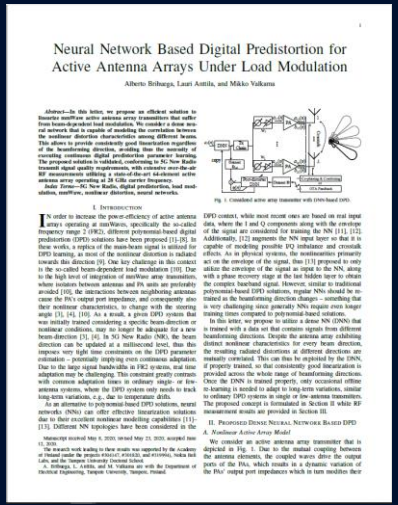
I. INTRODUCTION

With the arrival of the fifth-generation (5G) wireless communication system, the system capacity and communication rate are expected to increase significantly [1], [2]. And in order to meet the requirements of high capacity and high rate of the system, the signal will have wider bandwidth and more complex modulation, which will lead to a higher peak to average ratio (PAPR) seriously affecting the linearity and efficiency of radio frequency power amplifiers (RF PAs) with the inherent nonlinear characteristics. There are many approaches aiming to linearize the RF PA and keep a high efficiency at the same time, including feedback linearization [3], feedforward linearization [4], analog predistortion and digital predistortion (DPD) [5]. Among the linearization techniques, DPD is generally believed to be the most powerful linearization technology for its flexibility and high performance. At present, scholars and engineers are very interested in the accurate modeling and linearization of wideband RF PA.

Lots of DPD models have been proposed to compensate the nonlinearities of RF PAs [6]–[10]. Volterra-based models such as memory polynomial (MP) [6], generalized memory polynomial (GMP) [7] and dynamic deviation reduction Volterra (DDR) model [8] are the most widely used. Its virtue of the correlation of basis function of Volterra-based models, based on canonical piecewise-linear (CPWL) functions, decomposed vector rotation (DVR) is proposed to model the PAs with strong nonlinearity such as envelope tracking (ET) PAs [9]. Although these models have a good performance in narrowband, their linearization performance deteriorates to some extent with the increase of signal bandwidth. In addition, to meet the needs of the industry, many advanced PA architectures have been proposed, such as out-phasing PA, distributed PA and Doherty PA. Some of them may be quite different from the traditional PA in terms of

IEEE Access

(April 2020)


Neural Network Based Digital Predistortion for Active Antenna Arrays Under Load Modulation

Alberto Brihuega, Lauri Anttila, and Mikko Valkama

Abstract—In this letter, we propose an efficient solution to baseband digital predistortion, avoiding fine-tuning of the nonlinear distortion characteristics among different beams. This allows to provide consistently good linearization regardless of the beamforming direction, avoiding thus the necessity of executing continuous digital predistortion parameter learning. The proposed solution is validated, conforming to 5G New Radio transmit signal quality requirements, with extensive over-the-air RF measurements utilizing a state-of-the-art 64-element active antenna array operating at 28 GHz carrier frequency.

Index Terms—Active antenna, digital predistortion, load modulation, mmWave, nonlinear distortion, neural networks.

I. INTRODUCTION

In order to increase the power-efficiency of active antenna array operating at mmWaves, specifically the so-called frequency range 2 (FR2), different polynomial-based digital predistortion (DPD) solutions have been proposed [1]–[8]. In these works, a replica of the main-beam signal is utilized for DPD learning, as most of the nonlinear distortion is radiated towards this direction [9]. One key challenge in this context is the so-called beam-dependent load modulation [10]. Due to the high level of integration of mmWave array transmitters, where isolators between antennas and PA units are preferably avoided [10], the interactions between neighboring antennas cause the PA's output port impedance, and consequently also their nonlinear characteristics, to change with the steering angle [3], [4], [10]. As a result, a given DPD system that was initially trained considering a specific beam-direction or nonlinear conditions, may no longer be adequate for a new beam-direction [3], [4]. In 5G New Radio (NR), the beam direction can be updated at a millisecond level, thus this imposes very tight time constraints on the DPD parameter estimation, possibly requiring even continuous adaptation. Due to the large signal bandwidths in FR2 systems, real time adaptation may be challenging. This constraint greatly contrasts with common adaptation times in ordinary single- or few-antenna systems, where the DPD system only needs to track long-term variations, e.g., due to temperature drifts.

As an alternative to polynomial-based DPD solutions, neural networks (NNs) can offer effective linearization solutions due to their excellent nonlinear modelling capabilities [11]–[13]. Different NN topologies have been considered in the

Fig. 1. Considered active array transmitter with DSN-based DPD.

DPD context, while most recent ones are based on real input data, where the I and Q components along with the envelope of the signal are considered for training the NN [11], [12]. Additionally, [12] augments the NN input layer so that it is capable of modeling possible I/Q imbalance and crosstalk effects. As in physical systems, the nonlinearities primarily act on the envelope of the signal, thus [13] proposed to only utilize the envelope of the signal as input to the NN, along with a phase recovery stage at the last hidden layer to obtain the complex baseband signal. However, similar to traditional polynomial-based DPD solutions, regular NNs should be retrained in the beamforming direction changes – something that is very challenging since generally NNs require even longer training times compared to polynomial-based solutions.

In this letter, we propose to utilize a dense NN (DNN) that is trained with a data set that contains signals from different beamforming directions. Despite the antenna array exhibiting distinct nonlinear characteristics for every beam direction, the resulting radiated distortions at different directions are mutually correlated. This can thus be exploited by the DNN, if properly trained, so that consistently good linearization is provided across the whole range of beamforming directions. Once the DNN is trained properly, only occasional offline re-learning is needed to adapt to long-term variations, similar to ordinary DPD systems in single or few-antenna transmitters. The proposed concept is formulated in Section II while RF measurement results are provided in Section III.

II. PROPOSED DENSE NEURAL NETWORK BASED DPD

A. Nonlinear Active Array Model

We consider an active antenna array transmitter that is depicted in Fig. 1. Due to the mutual coupling between the antenna elements, the coupled waves drive the output ports of the PAs, which results in a dynamic variation of the PAs' output port impedances which in turn modifies their

Manuscript received December 20, 2019; revised March 15, 2020; accepted April 13, 2020. Date of publication June 4, 2020; date of current version September 2, 2020. This work was supported in part by the Academy of Finland under the projects 319437, 319994, and 328860, and in part by the Doctoral School, Tampere University. (Corresponding author: Mikko Valkama.)

Alberto Brihuega, Lauri Anttila, Mattias Turunen, Markus Allén, and Mikko Valkama are with the Department of Electrical Engineering, Tampere University, 33720 Tampere, Finland (e-mail: mikko.valkama@tuni.fi).

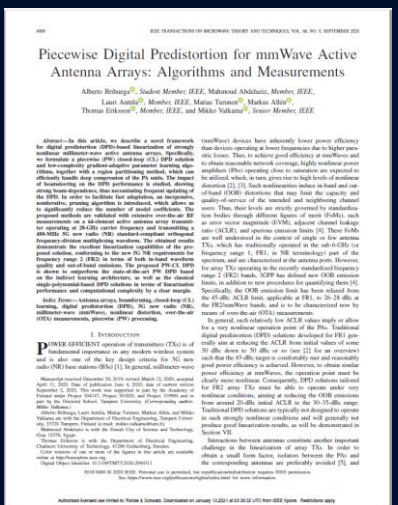
Marko Kosunen is with the Aalto University, 02150 Espoo, Finland.

Thomas Eriksson is with the Department of Electrical Engineering, Chalmers University of Technology, 41296 Gothenburg, Sweden.

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMTT.2020.2994311

(June 2020)


Piecewise Digital Predistortion for mmWave Active Antenna Arrays: Algorithms and Measurements

Alberto Brihuega[1], *Student Member, IEEE*, Mahmoud Abdelaziz, *Member, IEEE*, Lauri Anttila[2], *Member, IEEE*, Matias Turunen[2], Markus Allén[2], Thomas Eriksson[3], *Member, IEEE*, and Mikko Valkama[2], *Senior Member, IEEE*

Abstract—In this article, we describe a novel framework for digital predistortion (DPD)-based linearization of strongly nonlinear millimeter-wave active antenna arrays. Specifically, we formulate a piecewise (PW) closed-loop (CL) DPD solution and low-complexity gradient-adaptive parameter learning algorithm, which can be applied directly over-the-air (OTA) to efficiently handle deep compression of the PA units. The impact of beamsteering on the DPD performance is studied, showing strong beam-dependence, thus necessitating frequent updating of the DPD. In order to facilitate fast adaptation, an inexpensive, nondirective, pruning algorithm is introduced, which allows us to significantly reduce the number of model coefficients. The proposed methods are validated with extensive over-the-air RF measurements on a 64-element active antenna array transmitter operating at 28 GHz carrier frequency, utilizing a state-of-the-art 400-MHz 5G new radio (NR) standard-compliant orthogonal frequency-division multiplexing waveforms. The obtained results demonstrate the excellent linearization capabilities of the proposed solution, conforming to the new 5G NR requirements for frequency range 2 (FR2) in terms of both in-band waveform quality and out-of-band emissions. The proposed PW-CL DPD is shown to outperform the state-of-the-art PW DPD based on the indirect learning architecture, as well as the classical single-polynomial-based DPD solutions in terms of linearization performance and computational complexity by a clear margin.

Index Terms—Antenna arrays, beamforming, closed-loop (CL) learning, digital predistortion (DPD), 5G new radio (NR), millimeter-wave (mmWave), nonlinear distortion, over-the-air (OTA) measurements, piecewise (PW) processing.

I. INTRODUCTION

POWER-EFFICIENT operation of transmitters (TXs) is of fundamental importance in any modern wireless system and is also one of the key design criteria for 5G new radio (NR) base stations (BSs) [1]. In general, millimeter-wave (mmWave) devices have inherently lower power efficiency than devices operating at lower frequencies due to higher parasitic losses. Thus, to achieve good efficiency at mmWaves and to obtain reasonable network coverage, highly nonlinear power amplifiers (PAs) operating close to saturation are expected to be utilized, which, in turn, gives rise to high levels of nonlinear distortion [2], [3]. Such nonlinearities induce in-band and out-of-band (OOB) distortions that may limit the capacity and quality-of-service of the intended and neighboring channel users. Thus, their levels are strictly governed by standardization bodies through different figures of merit (FoMs), such as error vector magnitude (EVM), adjacent channel leakage ratio (ACLR), and spurious emission limits [4]. These FoMs are well understood in the context of single or few antenna TXs, which has traditionally operated in the sub-6-GHz (or frequency range 1, FR1, in NR terminology) part of the spectrum, and are characterized at the antenna port. However, for array TXs operating in the recently standardized frequency range 2 (FR2) bands, 3GPP has defined new OOB emission limits, in addition to new procedures for quantifying them [4]. Specifically, the OOB emission limit has been relaxed from the 45-dBc ACLR limit, applicable at FR1, to 20–28 dBc at the FR2/mmWave bands, and is to be characterized now by means of over-the-air (OTA) measurements.

In general, such relatively low ACLR values imply or allow for a very nonlinear operation point of the PAs. Traditional digital predistortion (DPD) solutions developed for FR1 generally aim at reducing the ACLR from initial values of some 30 dBc down to 50 dBc or so (see [2] for an overview) such that the 45-dBc target is comfortably met and reasonably good power efficiency is achieved. However, to obtain similar power efficiency at mmWaves, the operating point must be clearly more nonlinear. Consequently, DPD solutions tailored for FR2 array TXs must be able to operate under very nonlinear conditions, aiming at reducing the OOB emissions from around 25-dBc initial ACLR to the 30–35-dBc range. Traditional DPD solutions are typically not designed to provide in such strongly nonlinear conditions and will generally not produce good linearization results, as will be demonstrated in Section VII.

Interactions between antennas constitute another important challenge in the linearization of array TXs. In order to obtain a small form factor, isolators between the PAs and the corresponding antennas are preferably avoided [5], and

Manuscript received December 20, 2019; revised March 15, 2020; accepted April 13, 2020. Date of publication June 4, 2020; date of current version September 2, 2020. This work was supported in part by the Academy of Finland under the projects 319437, 319994, and 328860, and in part by the Doctoral School, Tampere University. (*Corresponding author: Mikko Valkama.*)

Alberto Brihuega, Lauri Anttila, Matias Turunen, Markus Allén, and Mikko Valkama are with the Department of Electrical Engineering, Tampere University, 33720 Tampere, Finland (e-mail: mikko.valkama@tuni.fi).

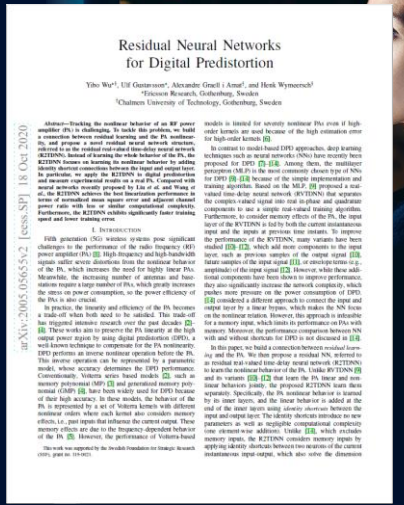
Marko Kosunen is with the Aalto University, 02150 Espoo, Finland.

Thomas Eriksson is with the Department of Electrical Engineering, Chalmers University of Technology, 41296 Gothenburg, Sweden.

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMTT.2020.2994311

(Sep 2020)


Residual Neural Networks for Digital Predistortion

Yibo Wu[1], Ulf Gustavsson[2], Alexandre Graell i Amat[1], and Henk Wymeersch[1]
[1]Ericsson Research, Gothenburg, Sweden
[2]Chalmers University of Technology, Gothenburg, Sweden

Abstract—Tracking the nonlinear behavior of an RF power amplifier (PA) is challenging. To tackle this problem, we build a connection between residual learning and the PA nonlinearity, and propose a novel residual neural network structure, referred to as the residual real-valued time-delay neural network (RES-TDNN). Instead of learning the whole behavior of the PA, the RES-TDNN focuses on learning its nonlinear behavior by adding identity shortcut connection between the input and output layer. In particular, we apply the RES-TDNN to digital predistortion and measure experimental results on a real PA. Compared with neural networks recently proposed by Liu et al. and Wang et al., the RES-TDNN achieves the best linearization performance in terms of normalized mean square error and adjacent channel power ratio with less or similar computational complexity. Furthermore, the RES-TDNN exhibits significantly faster training speed and lower training error.

I. INTRODUCTION

Fifth generation (5G) wireless systems pose significant challenges to the performance of the radio frequency (RF) power amplifier (PA) [1]. High frequency and high-bandwidth signals suffer severe distortions from the nonlinear behavior of the PA, which increases the need for highly linear PAs. Meanwhile, the increasing number of antennas and base stations require a large number of PAs, which greatly increases the stress on power consumption, so the power efficiency of the PAs is also crucial.

In practice, the linearity and efficiency of the PA becomes a trade-off when both need to be satisfied. This trade-off has triggered intensive research over the past decades [2]–[4]. These works aim to improve the PA linearity at the high output power region by using digital predistortion (DPD), a well-known technique to compensate for the PA nonlinearity. DPD performs an inverse nonlinear operation before the PA. This inverse operation can be represented by a parametric model, whose accuracy determines the DPD performance. Conventionally, Volterra series based models [2], such as memory polynomial (MP) [3] and generalized memory polynomial (GMP) [4], have been widely used for DPD because of their high accuracy. In these models, the behavior of the PA is represented by a set of Volterra kernels with different nonlinear orders where each kernel also considers memory effects, i.e., past inputs that influence the current output. These memory effects are due to the frequency-dependent behavior of the PA [5]. However, the performance of Volterra-based models is limited for severely nonlinear PAs even if high-order kernels are used because of the high estimation error for high-order kernels [6].

In contrast to model-based DPD approaches, deep learning techniques such as neural networks (NNs) have recently been proposed for DPD [7]–[14]. Among them, the multilayer perceptron (MLP) is the most commonly chosen type of NNs for DPD [8]–[11] because of the simple implementation and training algorithm. Based on the MLP, [8] proposed a real-valued time-delay neural network (RVTDNN) that separates the complex-valued signal into real in-phase and quadrature components to use a simple real-valued training algorithm. Furthermore, to consider memory effects of the PA, the input layer of the RVTDNN is fed by both the current instantaneous input and the inputs at previous time instants. To improve the performance of the RVTDNN, many variants have been studied [10]–[12], which add more comparisons to the input layer, such as previous samples of the output signal [10], future samples of the input signal [11], or envelope terms (e.g., amplitude) of the input signal [12]. However, while these additional components have been shown to improve performance, they also significantly increase the network complexity, which pushes more pressure on the power consumption of DPD. [10] considered a different approach to connect the input and output layer by a linear bypass, which makes the NN focus on the nonlinear relation. However, this approach is infeasible for a memory input, which limits its performance on PAs with memory. Moreover, the performance comparison between NN with and without shortcuts for DPD is not discussed in [10].

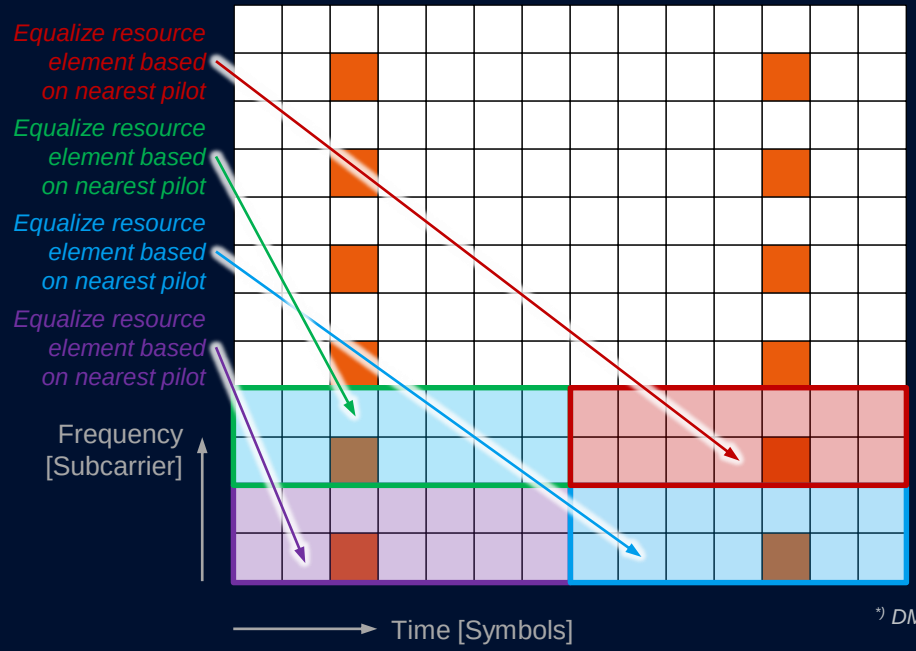
In this paper, we build a connection between *residual learning* and the PA nonlinearity and thus propose a residual NN, referred to as residual real-valued time-delay neural network (RES-TDNN) to learn the nonlinear behavior of the PA. Unlike RVTDNN [8] and its variants [10]–[12] that learn the PA linear and nonlinear behaviors jointly, the proposed RES-TDNN learns them separately. Specifically, the PA nonlinear behavior is learned by its inner layers, and the linear behavior is added at the end of the inner layers using *identity shortcuts* between the input and output layer. The identity shortcuts introduce no new parameters as well as negligible computational complexity (one element-wise addition). Unlike [10], which excludes memory inputs, the RES-TDNN considers memory inputs by applying identity shortcuts between two neurons of the current instantaneous input-output, which also solve the dimension

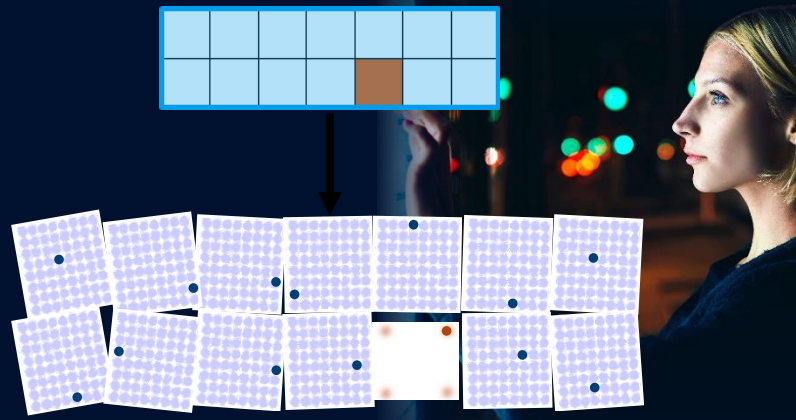
arXiv:2005.05655v2 [eess.SP] 18 Oct 2020

(Oct 2020)

PHASE 2: WHY IS THERE ROOM FOR MACHINE LEARNING TO BE APPLIED IN WIRELESS?

- 5G: there is a zoo of reference signals*) to allow the receiver to estimate the channel properties and ultimately equalize resource elements for the propagation effects

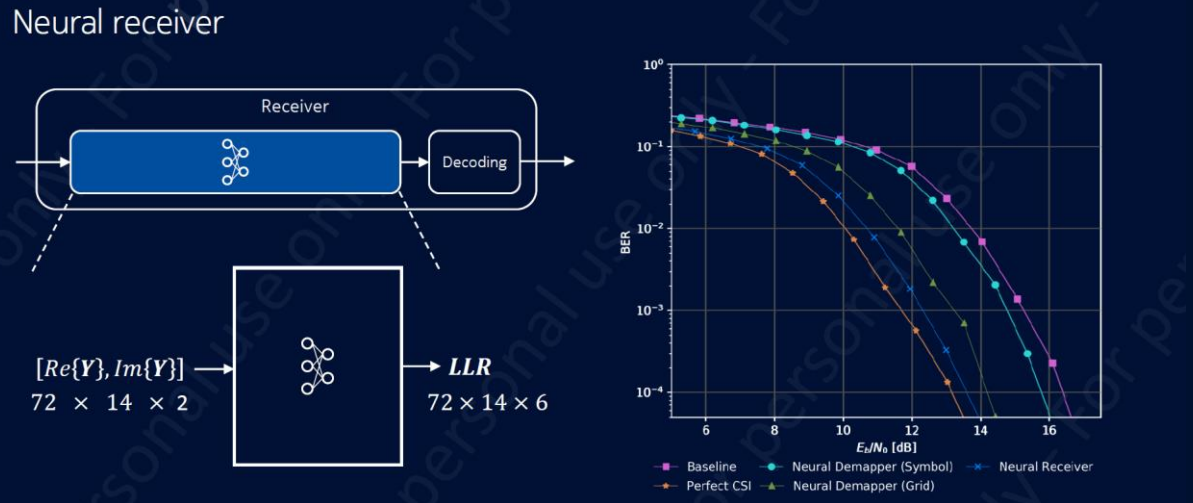




The imperfect channel estimation and channel aging leads to SNR degradation and mismatched computation and thus equalization errors → Machine Learning will help to overcome this mismatch!

*) DMRS for each physical channel in DL and UL direction, PTRS; DL: CSI-RS, TRS, PRS; UL: SRS

PHASE 2: APPROACHING PERFORMANCE CLOSE TO PERFECT CHANNEL KNOWLEDGE



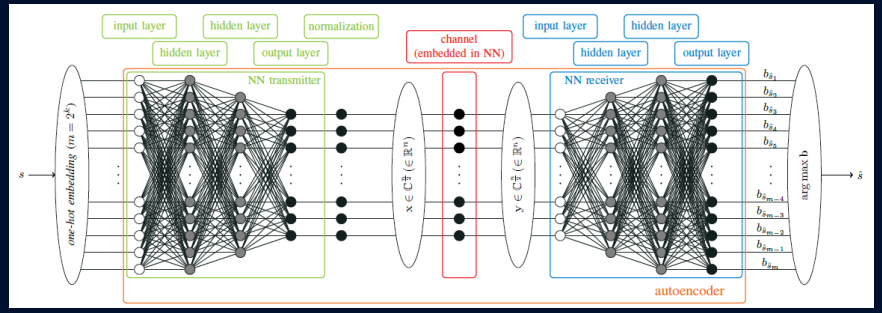
Data-aided channel estimation, equalization, and demapping for unprecedented performance

22/28

NOKIA Bell Labs

PHASE 3: AUTOENCODER?

- The autoencoder challenge
- Learning the behavior of an End-to-End (E2E) communication link via an autoencoder
  - One autoencoder or a concatenation of several autoencoder?

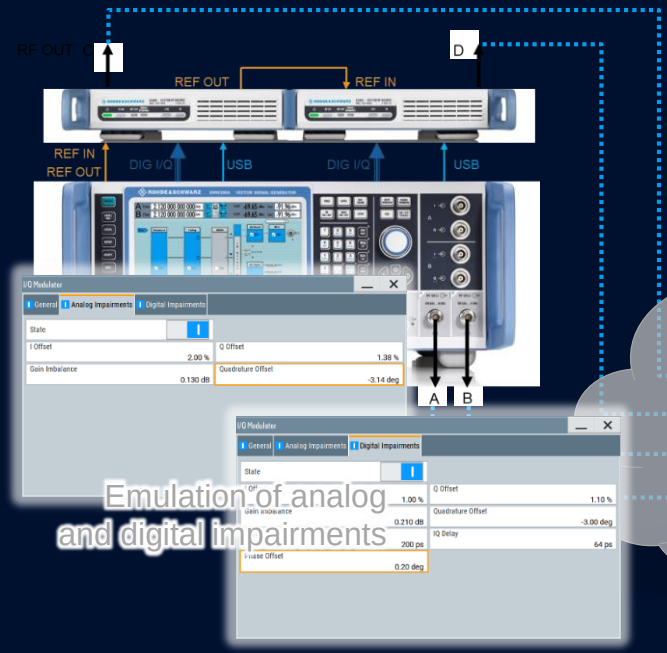


Source: [OFDM-Autoencoder for End-to-End learning of communication systems]

- Yes, provides additional performance gains & efficiency, e.g. can eliminate the need for transmission of pilot signals, but how practical is this solution in ‘real life’?

CAN T&M EQUIPMENT ACCOMPANY RESEARCH FOR MACHINE LEARNING?

► Sure, by Generating data (training) sets, emulating radio environments and providing real IQ data



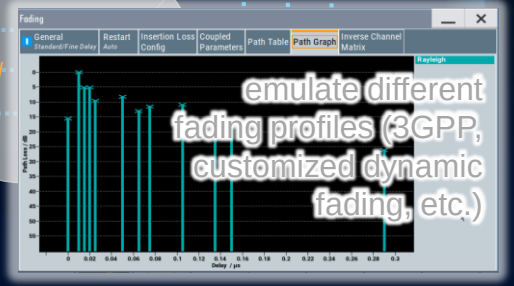
IQ capture via TCP/IP

PC with VSE software

ML model

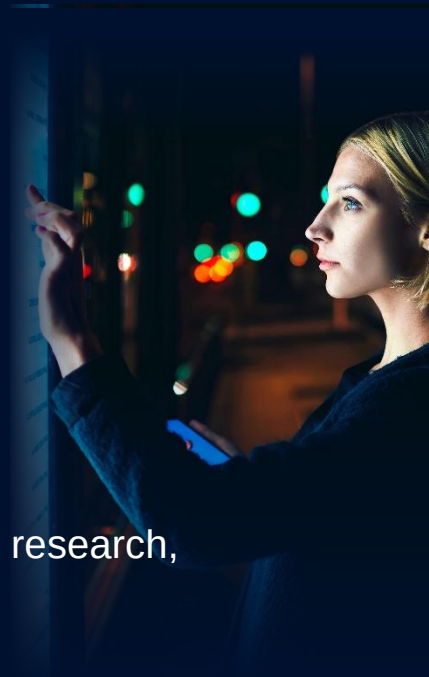
Radio Channel Characteristics

(represented by a standardized 3GPP fading profile)



SUMMARY

- Deployment of 5G networks is in full swing! Clear evolution path provided by the industry's standardization organization
- Academia and key industry players are exploring the boundaries and started looking into next generation of wireless communication aka 6G
- New, challenging technology components may complement the existing concept of cellular networks or even add additional revolutionary aspects
- R&S is already part of it and is actively engaged in this phase of fundamental research, providing our expertise in test and measurement to make ideas real



Thank you for your attention!

"If you want to go fast, go alone.
If you want to go far, go together!"

African proverb

#THINKSIX 6G

https://www.rohde-schwarz.com/us/knowledge-center/videos/-thinksix-main-6g-research-areas-video-detailpage_251220-1043073.html