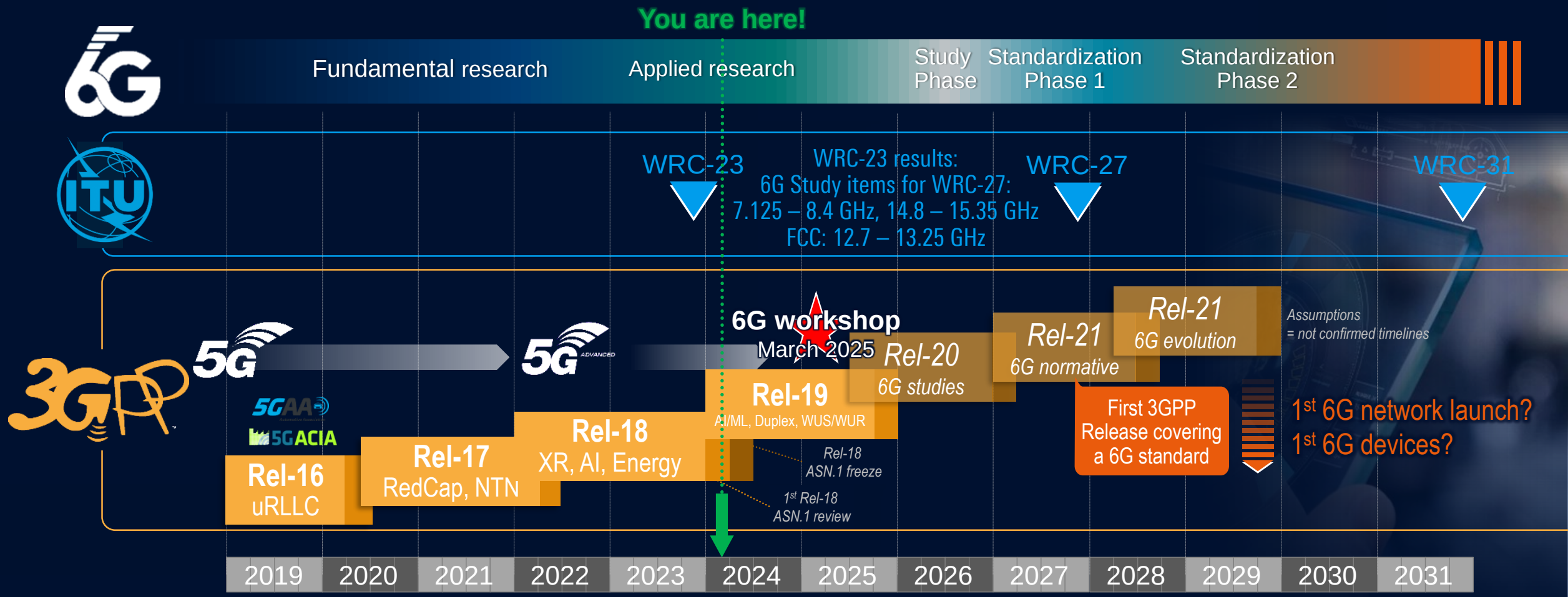
ON THE VERGE OF 6G?

Will AI/ML revolutionize wireless communication?

ROHDE&SCHWARZ

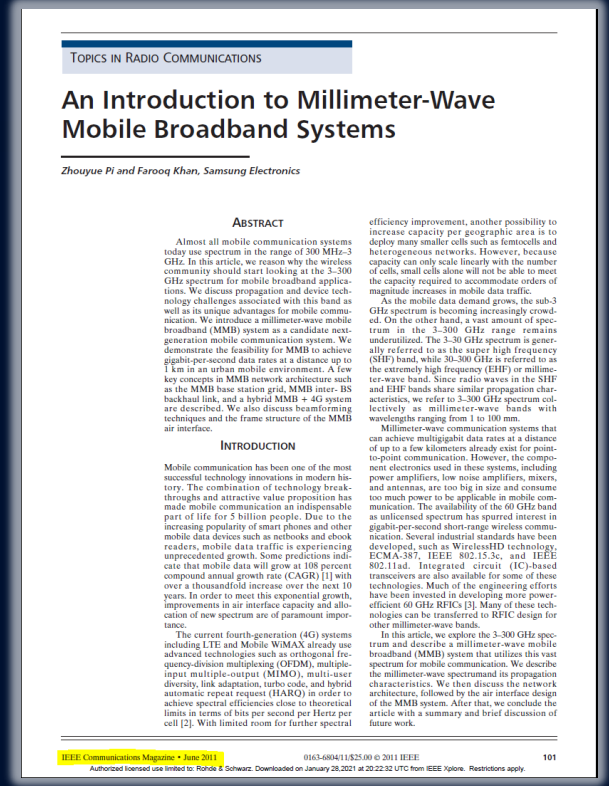
Make ideas real

LET'S START WITH TIMELINES
FUTURE STANDARDIZATION AND REGULATORY ROADMAP



[1] *IMT-2020 systems are called 5G, The ITU has already started a new technology trend report to prepare the work on "IMT-2020 and beyond" that is likely to become 6G*

LET'S START WITH TIMELINES
IS THIS THE RIGHT TIME TO TALK ABOUT 6G? YES!



TOPICS IN RADIO COMMUNICATIONS

An Introduction to Millimeter-Wave Mobile Broadband Systems

Zhouyue Pi and Farooq Khan, Samsung Electronics

ABSTRACT

Almost all mobile communication systems today use spectrum in the range of 300 MHz–3 GHz. In this article, we reason why the wireless community should start looking at the 3–300 GHz spectrum for mobile broadband applications. We discuss propagation and device technology challenges associated with this band as well as its unique advantages for mobile communication. We introduce a millimeter-wave mobile broadband (MMB) system as a candidate next-generation mobile communication system. We demonstrate the feasibility for MMB to achieve gigabit-per-second data rates at a distance up to 1 km in an urban mobile environment. A few key concepts in MMB network architecture such as the MMB base station grid, MMB inter-BS backhaul link, and a hybrid MMB + 4G system are described. We also discuss beamforming techniques and the frame structure of the MMB air interface.

INTRODUCTION

Mobile communication has been one of the most successful technology innovations in modern history. The combination of technology breakthroughs and attractive value proposition has made mobile communication an indispensable part of life for 5 billion people. Due to the increasing popularity of smart phones and other mobile data devices such as netbooks and ebook readers, mobile data traffic is experiencing unprecedented growth. Some predictions indicate that mobile data will grow at 108 percent compound annual growth rate (CAGR) [1] with over a thousandfold increase over the next 10 years. In order to meet this exponential growth, improvements in air interface capacity and allocation of new spectrum are of paramount importance.

The current fourth-generation (4G) systems including LTE and Mobile WiMAX already use advanced technologies such as orthogonal frequency-division multiplexing (OFDM), multiple-input multiple-output (MIMO), multi-user diversity, link adaptation, turbo code, and hybrid automatic repeat request (HARQ) in order to achieve spectral efficiencies close to theoretical limits in terms of bits per second per Hertz per cell [2]. With limited room for further spectral efficiency improvement, another possibility to increase capacity per geographic area is to deploy many smaller cells such as femtocells and heterogeneous networks. However, because capacity can only scale linearly with the number of cells, small cells alone will not be able to meet the capacity required to accommodate orders of magnitude increases in mobile data traffic.

As the mobile data demand grows, the sub-3 GHz spectrum is becoming increasingly crowded. On the other hand, a vast amount of spectrum in the 3–300 GHz range remains underutilized. The 3–30 GHz spectrum is generally referred to as the super high frequency (SHF) band, while 30–300 GHz is referred to as the extremely high frequency (EHF) or millimeter-wave band. Since radio waves in the SHF and EHF bands share similar propagation characteristics, we refer to 3–300 GHz spectrum collectively as millimeter-wave bands with wavelengths ranging from 1 to 100 mm.

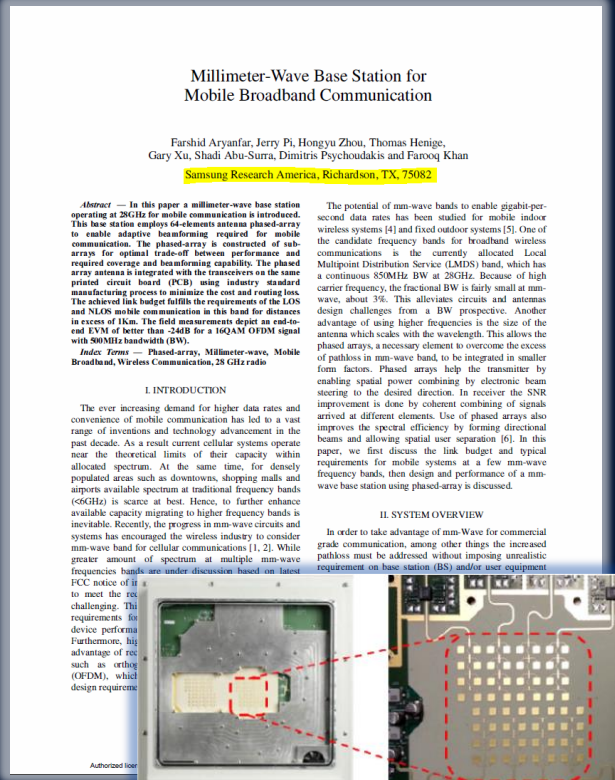
Millimeter-wave communication systems that can achieve multigigabit data rates at a distance of up to a few kilometers already exist for point-to-point communication. However, the component electronics used in these systems, including power amplifiers, low noise amplifiers, mixers, and antennas, are too big in size and consume too much power to be applicable in mobile communication. The availability of the 60 GHz band as unlicensed spectrum has spurred interest in gigabit-per-second short-range wireless communication. Several industrial standards have been developed, such as WirelessHD technology, ECMA-387, IEEE 802.15.3c, and IEEE 802.11ad. Integrated circuit (IC)-based transceivers are also available for some of these technologies. Much of the engineering efforts have been invested in developing more power-efficient 60 GHz RFICs [3]. Many of these technologies can be transferred to RFIC design for other millimeter-wave bands.

In this article, we explore the 3–300 GHz spectrum and describe a millimeter-wave mobile broadband (MMB) system that utilizes this vast spectrum for mobile communication. We describe the millimeter-wave spectrumand its propagation characteristics. We then discuss the network architecture, followed by the air interface design of the MMB system. After that, we conclude the article with a summary and brief discussion of future work.

IEEE Communications Magazine • June 2011 0163-6804/11/$25.00 © 2011 IEEE

The support of mmWave was one of the revolutionary elements in 5G!

~4 years



Millimeter-Wave Base Station for Mobile Broadband Communication

Farshid Aryanfar, Jerry Pi, Hongyu Zhou, Thomas Henige, Gary Xu, Shadi Abu-Surra, Dimitris Psychoudakis and Farooq Khan

Samsung Research America, Richardson, TX, 75082

***Abstract* — In this paper a millimeter-wave base station operating at 28GHz for mobile communication is introduced. This base station employs 64-elements antenna phased-array to enable adaptive beamforming required for mobile communication. The phased-array is constructed of sub-arrays for optimal trade-off between performance and required coverage and beamforming capability. The phased array antenna is integrated with the transceivers on the same printed circuit board (PCB) using industry standard manufacturing process to minimize the cost and routing loss. The achieved link budget fulfills the requirements of the LOS and NLOS mobile communication in this band for distances in excess of 1Km. The field measurements depict an end-to-end EVM of better than -24dB for a 16QAM OFDM signal with 500MHz bandwidth (BW).**

***Index Terms* — Phased-array, Millimeter-wave, Mobile Broadband, Wireless Communication, 28 GHz radio**

I. INTRODUCTION

The ever increasing demand for higher data rates and convenience of mobile communication has led to a vast range of inventions and technology advancement in the past decade. As a result current cellular systems operate near the theoretical limits of their capacity within allocated spectrum. At the same time, for densely populated areas such as downtowns, shopping malls and airports available spectrum at traditional frequency bands (<6GHz) is scarce at best. Hence, to further enhance available capacity migrating to higher frequency bands is inevitable. Recently, the progress in mm-wave circuits and systems has encouraged the wireless industry to consider mm-wave band for cellular communications [1, 2]. While greater amount of spectrum at multiple mm-wave frequencies bands are under discussion based on latest FCC notice of it

The potential of mm-wave bands to enable gigabit-per-second data rates has been studied for mobile indoor wireless systems [4] and fixed outdoor systems [5]. One of the candidate frequency bands for broadband wireless communications is the currently allocated Local Multipoint Distribution Service (LMDS) band, which has a continuous 850MHz BW at 28GHz. Because of high carrier frequency, the fractional BW is fairly small at mm-wave, about 3%. This alleviates circuits and antennas design challenges from a BW prospective. Another advantage of using higher frequencies is the size of the antenna which scales with the wavelength. This allows the phased arrays, a necessary element to overcome the excess of pathloss in mm-wave band, to be integrated in smaller form factors. Phased arrays help the transmitter by enabling spatial power combining by electronic beam steering to the desired direction. In receiver the SNR improvement is done by coherent combining of signals arrived at different elements. Use of phased arrays also improves the spectral efficiency by forming directional beams and allowing spatial user separation [6]. In this paper, we first discuss the link budget and typical requirements for mobile systems at a few mm-wave frequency bands, then design and performance of a mm-wave base station using phased-array is discussed.

II. SYSTEM OVERVIEW

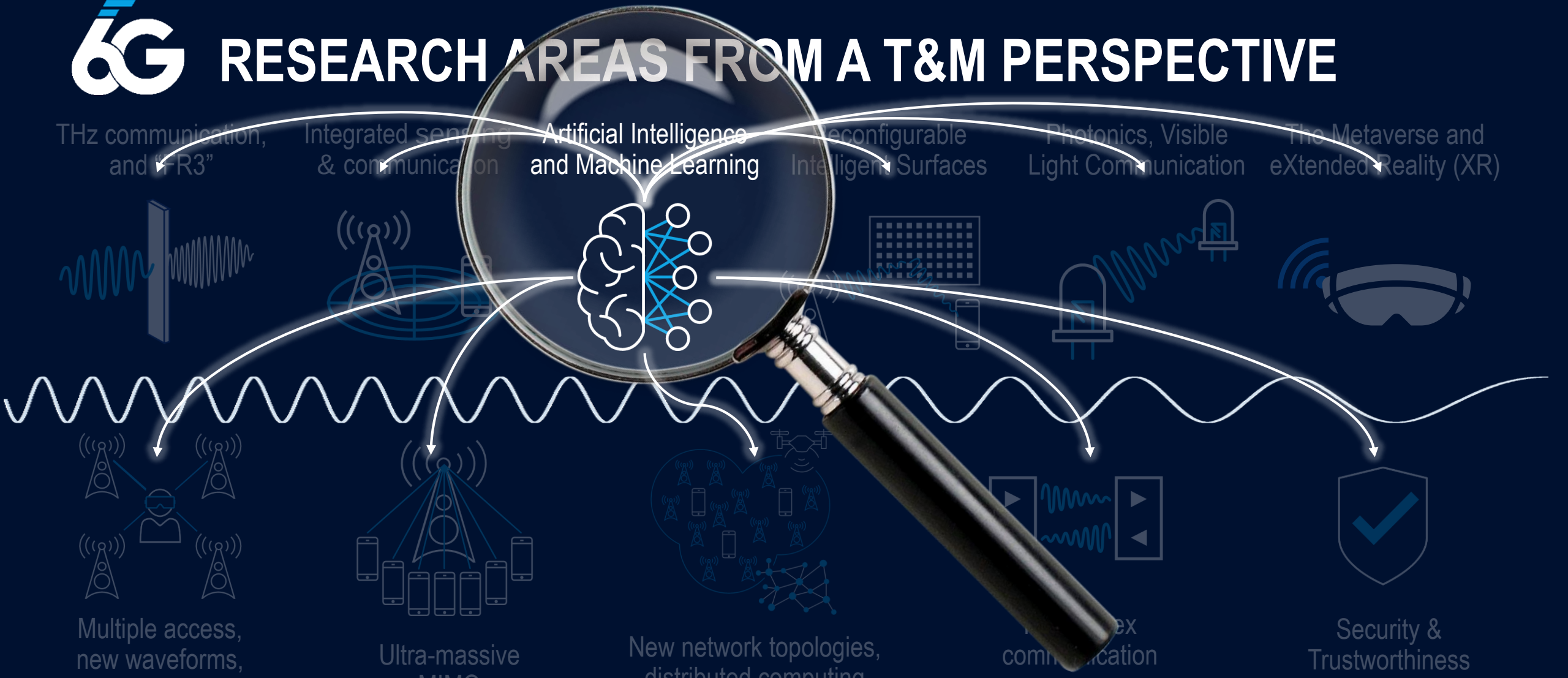
In order to take advantage of mm-Wave for commercial grade communication, among other things the increased pathloss must be addressed without imposing unrealistic requirement on base station (BS) and/or user equipment

28 GHz base station with 64-element antenna array

~4+ years

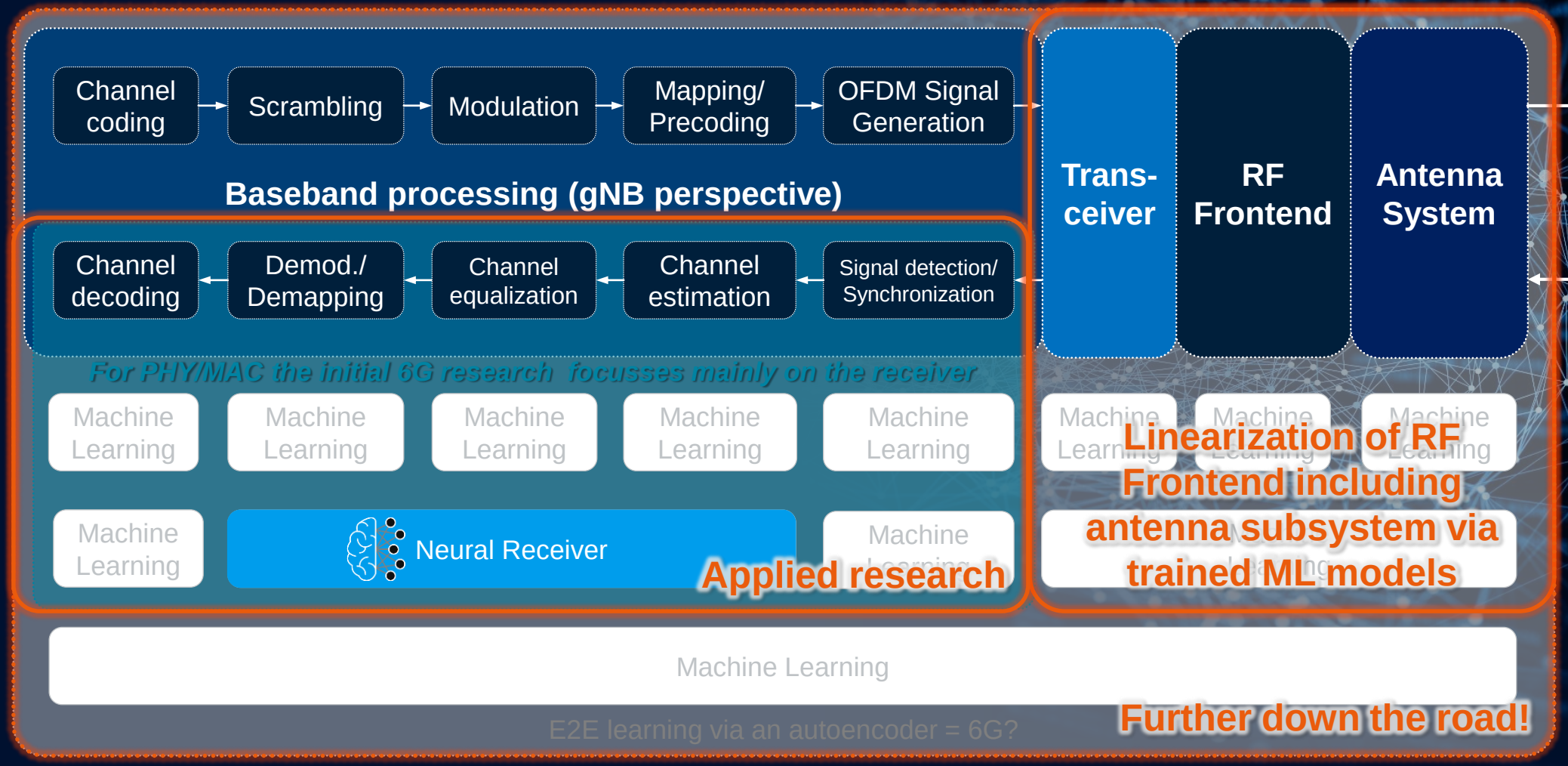
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5783993 *(June 2011)*
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7166778&tag=1 *(June 2015)*

RESEARCH AREAS FROM A T&M PERSPECTIVE



A high-level overview of all these research areas is provided in one of our #THINKSIX videos

TOWARDS AN AI-NATIVE AIR INTERFACE FOR 6G



ML applied to individual processing blocks

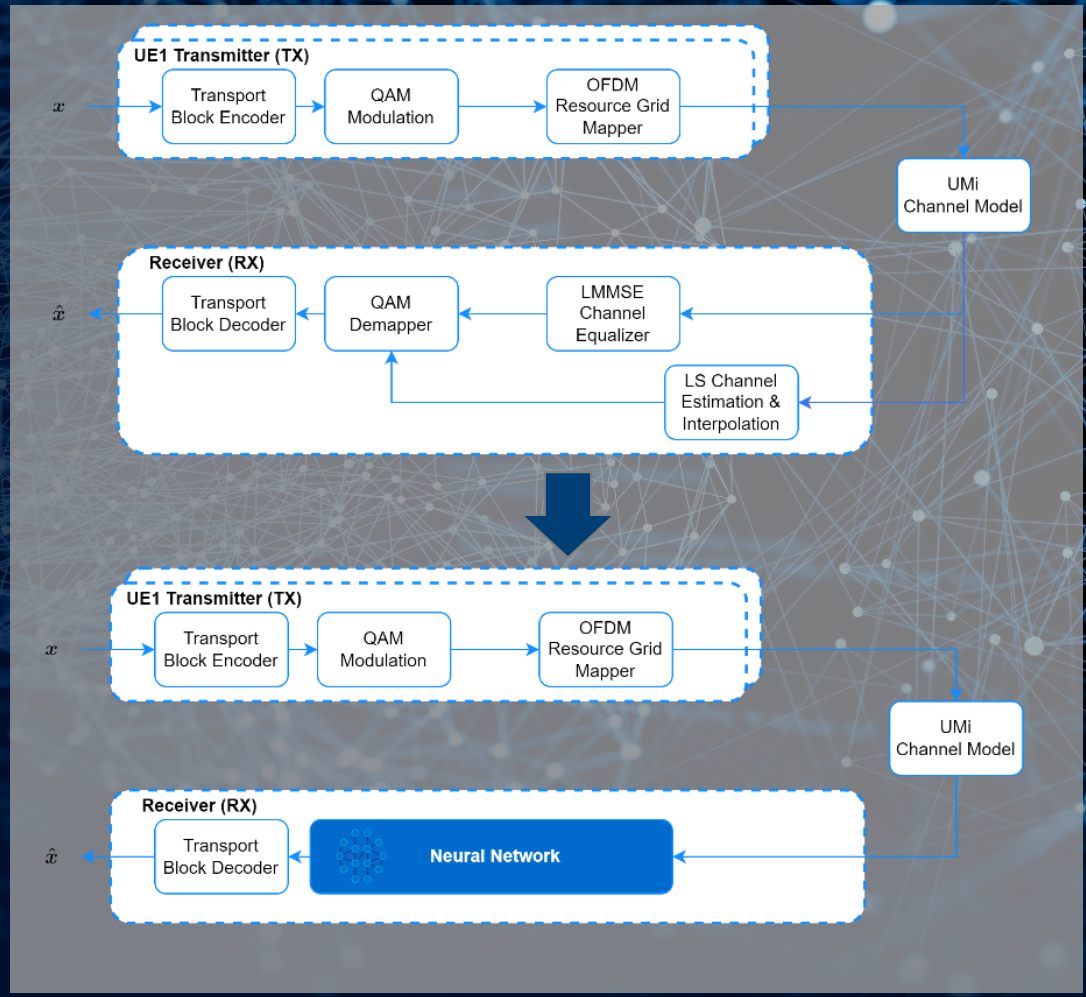
ML replaces multiple processing blocks

ML used to jointly optimize TX, RX and baseband processing;

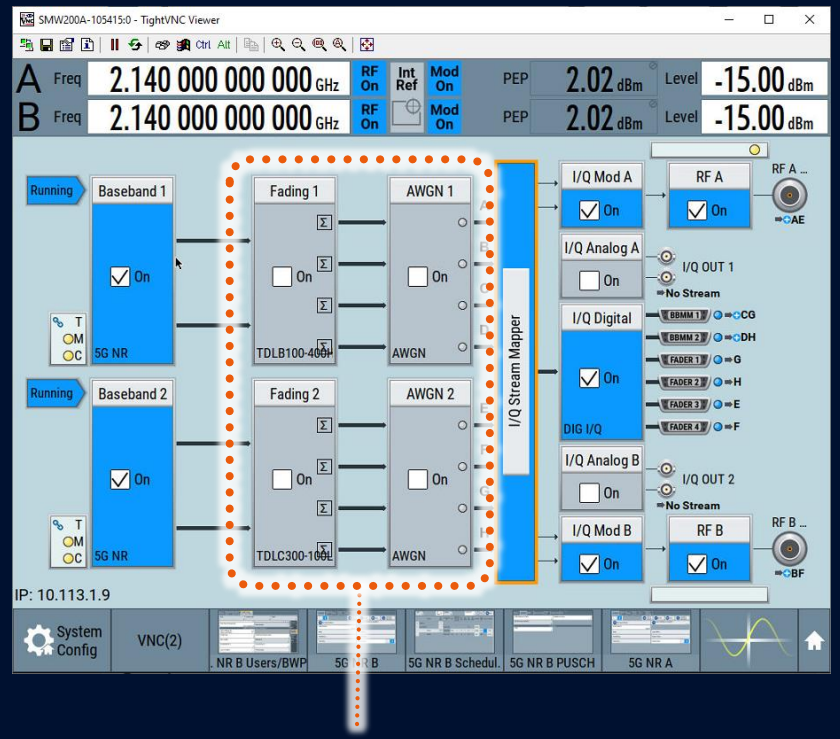
ML designs part of 6G PHY/MAC itself

NEURAL RECEIVER TESTBED

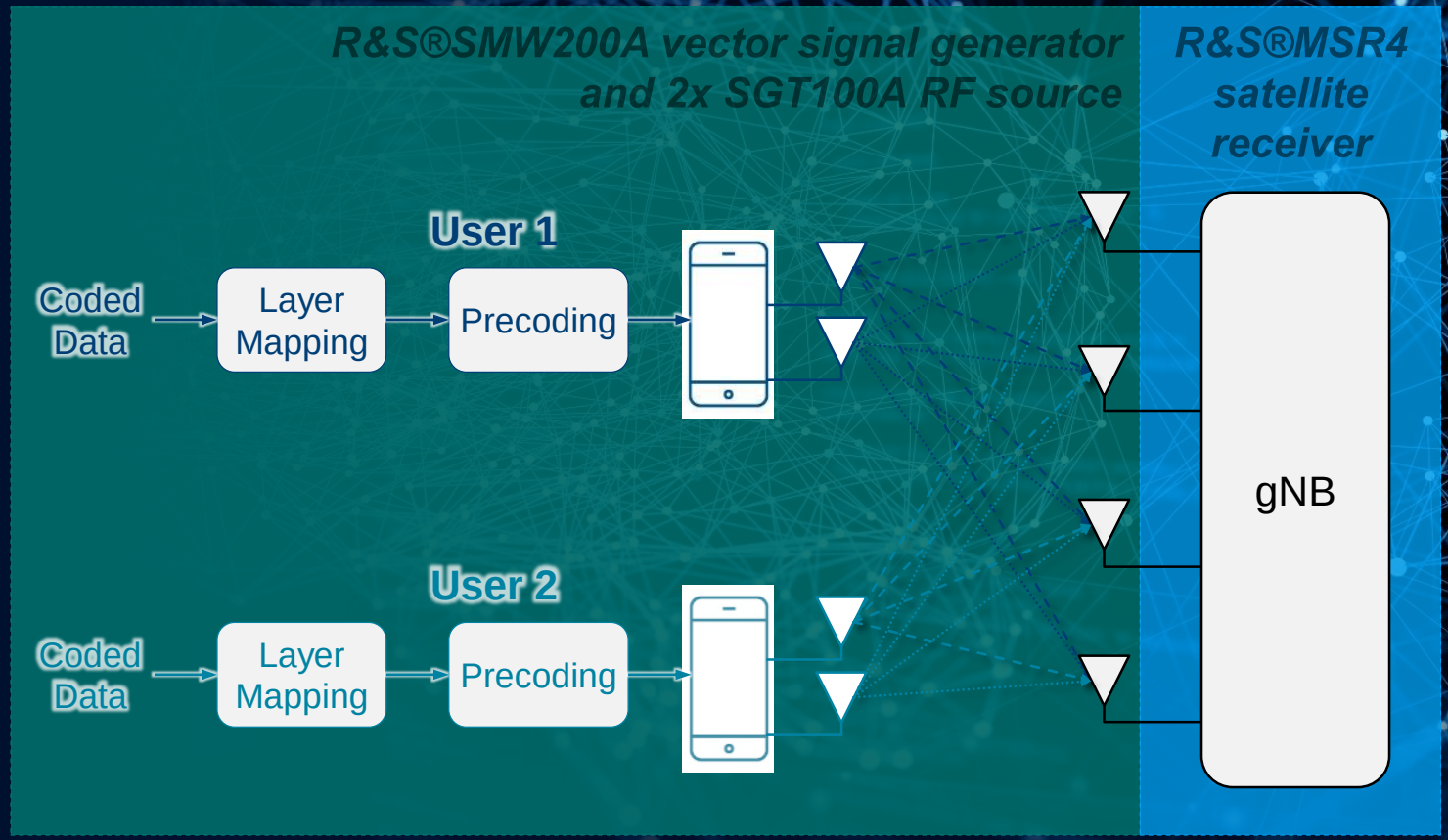
- Neural receiver: replacing conventional Digital Signal Processing (DSP) by AI/ML models
- Partnered up with **NVIDIA** to build industry-first neural receiver testbed
- 5G NR signal generation, receiving, pre-processing by **Rohde&Schwarz test & measurement solutions**
- Design of a neural receiver based on NVIDIA‘s **SIONNA™** open software framework: MIMO detection, channel estimation, equalization, demapping



TEST SCENARIO: 5G NR PUSCH MU-MIMO
NUMBER OF USERS, MIMO MODE AND NUMBER OF LAYERS



Both users independently faded, independent noise settings



Both users transmit simultaneously on 80 MHz signal bandwidth (PRB 217), 16QAM modulation
DMRS symbols 2 and 11, User#1 on even-numbered subcarriers, user#2 on odd-numbered subcarriers

NEURAL RECEIVER TESTBED
DEMONSTRATED @ MWC BARCELONA 2023

ROHDE&SCHWARZ
Make ideas real

SCPI
gRPC
Conducted

Signal Generator
2 Users
R&S®SMW200A
R&S®SGT100A (2x)

Signal Receiver
4 RX Antennas
R&S®MSR4
Satellite Receiver

4x SFP
10 Gb/s

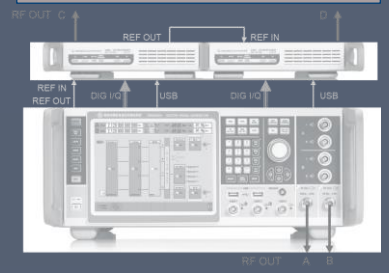
Streamed
I/Q

Onboard NIC
Orchestrator
http / REST
INTEL E810
5G UL Measurement
R&S®Server-Based Testing (SBT)
Server 2x AMD EPYC 7313 16-Core Processor

Onboard NIC
1 Gb/s

Visualization
Neural Receiver (Sionna™)
NVIDIA Server

Constellation Diagram Symbol Coordinates

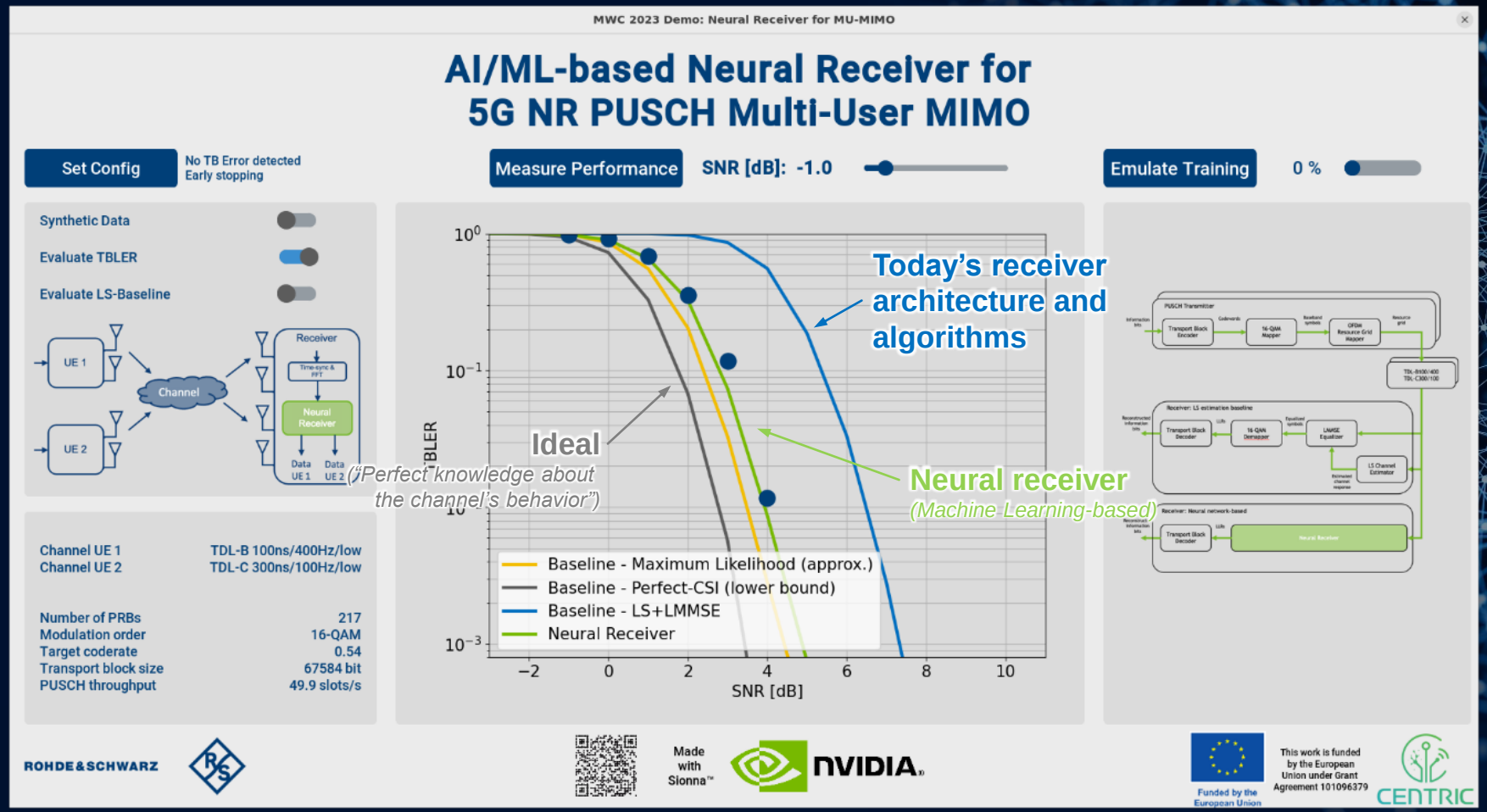


R&S®MSR4 Multi-purpose satellite receiver (Link)

Server-Based Testing (SBT) architecture and toolchain with VSE micro services runs on a Dell Precision 7920 with Debian Buster 10.10

Nvidia RTX4090

HARDWARE-IN-THE-LOOP VALIDATION OF A NEURAL RECEIVER IMPLEMENTATION



6G NEURAL RECEIVER TESTBED
APPLICATION VIDEO

- YouTube link: https://youtu.be/BQyxBYzdq5k
- IEEE conference paper: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10464486

2023 IEEE Globecom Workshops (GC Wkshps): Artificial Intelligence Enabled Next Generation Wireless Networks

A Neural Receiver for 5G NR Multi-user MIMO

Sebastian Cammerer[1], Fayçal Aït Aoudia[1], Jakob Hoydis[1], Andreas Oeldemann[2], Andreas Roessler[2], Timo Mayer[2], and Alexander Keller[1]

[1]NVIDIA, [2]Rohde & Schwarz, contact: scammerer@nvidia.com

***Abstract*—We introduce a neural network (NN)-based multi-user multiple-input multiple-output (MU-MIMO) receiver with 5G New Radio (5G NR) physical uplink shared channel (PUSCH) compatibility. The NN architecture is based on convolution layers to exploit the time and frequency correlation of the channel and a graph neural network (GNN) to handle multiple users. The proposed architecture adapts to an arbitrary number of sub-carriers and supports a varying number of multiple-input multiple-output (MIMO) layers and users without the need for any retraining. The receiver operates on an entire 5G NR *slot*, i.e., processes the entire received orthogonal frequency division multiplexing (OFDM) time-frequency resource grid by jointly performing channel estimation, equalization, and demapping. The proposed architecture operates less than 1 dB away from a baseline using linear minimum mean square error (LMMSE) channel estimation with K-best detection but benefits from a significantly lower computational complexity. We show the importance of a carefully designed training process such that the trained receiver is universal for a wide range of different unseen channel conditions. Finally, we demonstrate the results of a hardware-in-the-loop verification based on 3GPP compliant conformance test scenarios.**

I. Introduction

Artificial intelligence (AI) and machine learning (ML) have become ubiquitous tools in the wireless research community [1], [2] as well as the telecommunications industry [3]. This trend has been further accelerated by the recent announcement of the 3rd Generation Partnership Project (3GPP) consortium to investigate AI/ML in the physical layer as new study item for the upcoming 3GPP release 18 [3]. While this will most likely require disruptive changes in the signal structures and the transmitter implementation, our approach takes a different direction and focuses on neural network (NN)-based receivers which are fully compliant with 5G New Radio (5G NR). We emphasize that neural receivers can be seen as enabling technology for various novel applications such as site-specific basestations that can be re-trained after deployment as well as pilotless communications [4].

The concept of such a neural receiver was first proposed in [1] where the authors have demonstrated a performance close to that of a *classical* receiver with perfect channel state information (CSI) in a single-input multiple-output (SIMO) system by enabling joint channel estimation and data reconstruction. Note that earlier, the authors of [5] proposed convolutional neural network (CNN)-based receiver algorithms for OFDM detection. The neural receiver idea was extended to multiple-input multiple-output (MIMO) systems in [6]. It was shown later in [4], that a similar architecture also permits pilotless communications when combined with end-to-end learning [2]. Further, neural receivers for internet of things (IoT) applications have been demonstrated [7]. However, when considering deep learning for multi-user multiple-input multiple-output (MU-MIMO) systems [8]–[11], often perfect CSI has been assumed, neglecting the issue of implicit channel estimation. In addition, it is unclear whether evaluations performed on simplistic channel models generalize to more challenging channel environments.

In this work, we extend the concept of neural receivers by a flexible MU-MIMO component with 5G NR physical uplink shared channel (PUSCH) compatibility. A specific focus of the NN architecture is on the flexibility with respect to a varying number of users and a configurable number of sub-carriers. The NN architecture itself is a combination of graph neural network (GNN) and CNN layers. Intuitively, the GNN offers flexibility regarding varying number of users as it allows an easy reconfiguration similar to [10]. As a result, approximately 730k trainable weights are required to process an entire 5G NR slot, meaning the entire time/frequency resources consisting of thousands of resource elements in the time-frequency grid of an orthogonal frequency division multiplexing (OFDM) system. The number of physical resource blocks (PRBs) is also variable – in fact, our receiver is trained for 4 PRBs but evaluated for 217 PRBs. This flexibility is a key enabler for practical deployment as the proposed architecture neither requires any retraining if a different number of users is scheduled, nor if the number of allocated sub-carriers changes.

A practical challenge is to train the system such that it does not overfit to the underlying dataset or channel model. We therefore randomize the channel during training by using system level 3GPP urban microcell (UMi) channel models with random user drops to ensure that the learned receiver generalizes to unseen channel conditions. The neural receiver and our experiments are implemented using Sionna [12].

II. Neural Multi-user MIMO OFDM Receiver

We consider a MU-MIMO OFDM communication system in which N_{T} MIMO *layers*[1] are simultaneously transmitted on the same physical resources to a single receiver with N_{RX} receive antennas. We assume a total number of N_{TX} transmit antennas. Such a communication system is illustrated in Fig. 1.

This work has received financial support from the European Union under Grant Agreement 101096379 (CENTRIC). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission (granting authority). Neither the European Union nor the granting authority can be held responsible for them.

[1]In 5G NR, each user – possibly equipped with multiple antennas – can be configured to transmit multiple MIMO *layers* (or data *streams*). For readability, we denote every layer as an independent transmitter in the following description. The proposed neural receiver architecture supports multiple layers per user by treating every stream as a (virtual) user.

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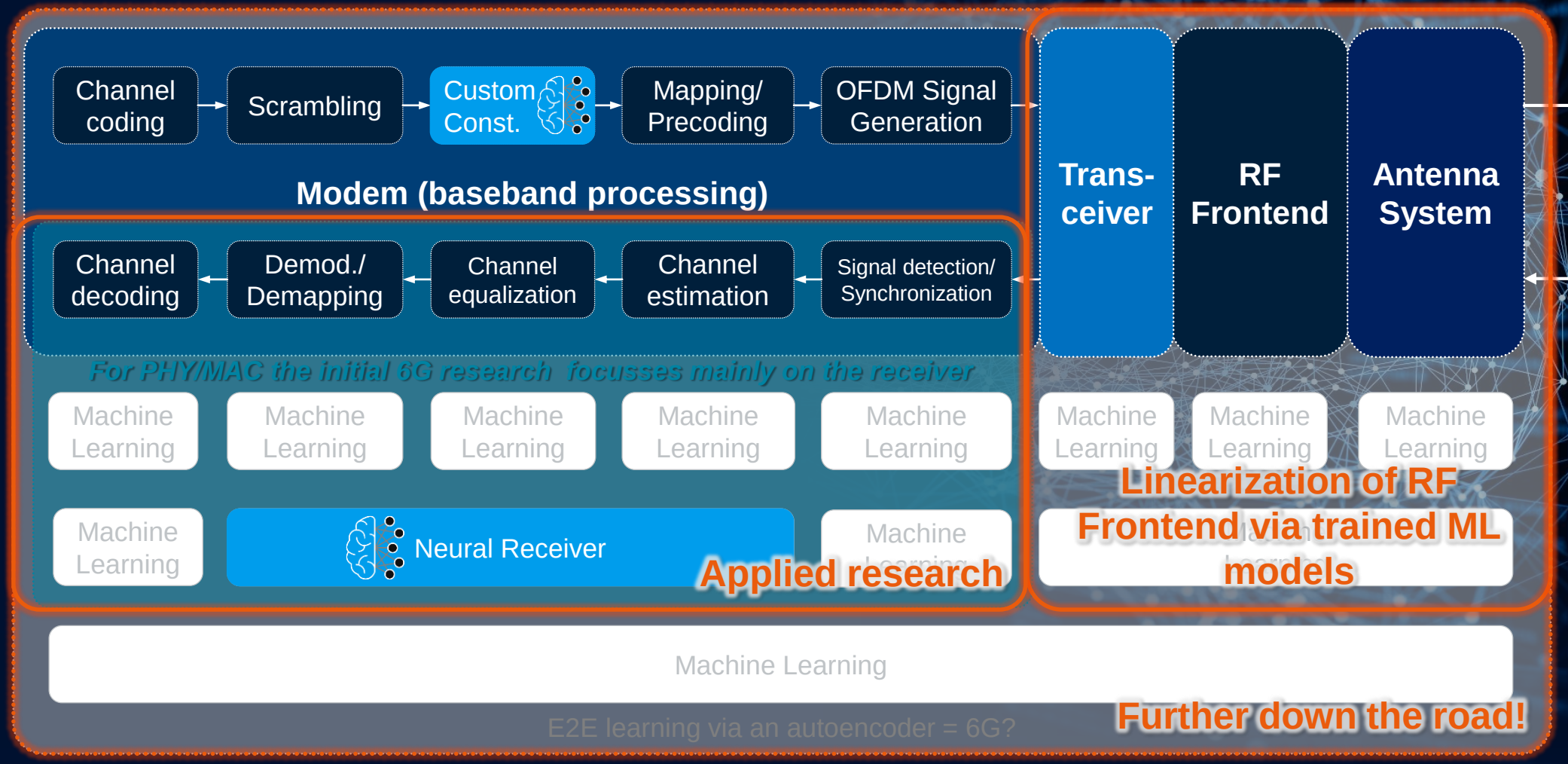
ENHANCING THE NEURAL RECEIVER?
TOWARDS AN AI-NATIVE AIR INTERFACE FOR 6G



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

NEURAL RECEIVER WITH CUSTOM MODULATION

Our conclusion

ADOPTION OF AI/ML REQUIRES ADAPTATION OF NEW TESTING METHODOLOGIES AND TEST PROCEDURES

- 3GPP Rel-18 and 19 lay the foundation for an AI/ML framework in 3GPP that 6G may build on.
- We demonstrated first promising results of replacing traditional signal processing blocks and classic signal processing algorithms with trained machine learning models
- Still a long way to go; several research challenges are currently under investigation by multiple research projects worldwide, e.g.:
  - Processing power, power consumption, etc.: implementation in GPU vs. FPGA or ASIC?
  - Training with synthetic data only? How to move to entirely real-world data-driven models?
  - Wireless radio channel characteristic representation in the form of fading profiles vs. real-time channel
  - Local adaptation of default models: “online training” in the field = site-specific neural receiver model
- The R&S testbed for neural receiver can help to validate performance of initial concepts before putting them into silicon.

THANK YOU!
QUESTIONS?

“No one can whistle a symphony. It takes a whole orchestra to play it.”

Halfrod E. Luccock (1885-1960)