D-Band Radio Solutions For Beyond 5G Reconfigurable Meshed Cellular Networks

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Abstract— **This paper presents a study of the D-band radio solutions, with beam-steering functionality, intended for use in the reconfigurable meshed network. The regulation and radio network constraints defining the specifications of a D-Band transceiver are reviewed. The architecture of the radio link is proposed and key enabling technologies needed to build the D-band transceiver are presented. The proposed solutions can be used for plenty of different radio connections, since they can provide a capacity level up to 100 Gbps over 160 meter and, at reduced capacity, hop lengths exceeding 1 km.**

***Index Terms*—5G, backhaul, link budget, mm-wave, D-Band, radio link.**

I. Introduction

DATA rates in wireless communications have been increasing exponentially over recent decades. For the upcoming decade, this trend seems to be unbroken. This poses several new challenges to the network infrastructure, especially when the network relies on a radio solution [1]. A radio backhaul transport network intended to work close to the access part in 5G and beyond-5G networks will need to meet the following requirements [2]–[4]:

- capacity up to 100 Gbit/s (50 Gbit/s go + 50 Gbit/s return)
- connection availability better than 99.9 %
- latency lower than 0.1 ms

The requirement of hundred Gbit/s demands the use of high spectrally efficient quadrature amplitude modulations (QAM), spatial diversity technology (LoS-MIMO) and, above all, large bandwidths, which are available only in the high millimetre-wave and sub-terahertz regions [4], [5]. The D-Band, ranging from 130 to 170 GHz, offers a vast bandwidth and it is now being considered as a candidate for high capacity links for 5G and beyond [7].

A benefit of operating in the high millimetre-wave and sub-terahertz regions of the spectrum is that phased-arrays can be built within a compact size and form-factor. This can be exploited to provide the radio links with beam-steering capabilities. This beam-steering capability can facilitate installation and setup. Moreover, it can provide flexibility and reconfigurability to the network. If each node can be reached from any other node by at least two different paths, the capacity and/or availability requirements of each single radio connection can be relaxed [6]. Moreover, the reconfigurability of the network can be exploited to bypass failing links due to weather conditions or occasionally obstructions, thus increasing substantially the network reliability.

Firstly, the paper reviews the regulation and radio network constraints that define the specifications of a base-line D-Band transceiver intended to meet the requirements of a reconfigurable meshed backhaul network. Then, the paper presents the architecture proposed and some of the key enabling technologies needed to build the D-band transceiver.

II. D-Band Radio Constraints

A. Regulation Constraints

According to the ECC Recommendation [7], only some portions of the D-Band spectrum will be actually available, because other portions are reserved for different services. This fragmentation of the available spectrum has a key impact on the possible architecture of the radio link.

Table I summarizes the results of the analysis of different radio architectures meeting the 100 Gbit/s capacity requirement [6]. The table shows the portions of the spectrum available according to the regulation, considering also the required 125 MHz guard-bands in each portion. Four radio solutions are studied for reaching the 100Gbps: a single transceiver approach; two parallel transceivers operating in two different channels and supporting each 1/2 of the required capacity; the use of polarization or spatial diversity to multiplex two streams in the same frequency channel exploiting a cross-polar canceller (XPIC) or LoS-MIMO 2x2 and the use of a 4th order diversity in a LoS-MIMO 4x4 to multiplex 4 streams with 1/4 of the required capacity. For each radio architecture, the

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TABLE I. ANALYSIS FOR 100 GBIT/S & 256-QAM SOLUTIONS IN D-BAND.

100Gbps	256 QAM	D-Band: 130–134 GHz (3.75 GHz)	141–149 GHz (7.25GHz)	152–163 GHz (12.25GHz)	167–175 GHz (7.55GHz)	Single connection feasibility	Node feasibility
Single transceiver 1+0							
TDD	16.0 GHz					Ko	Ko
FDD	2 X 8.0 GHz					Ko	Ko
fFDD	2 X 8.0 GHz					Ko	Ko
FD	8.0 GHz					ok	Ko
2 x parallel links							
TDD	2 X 8.0 GHz					Ko	Ko
FDD	2 x 2 X 4.0 GHz					Ko	Ko
fFDD	2 x 2 X 4.0 GHz					Ko	Ko
FD	2 X 4.0 GHz					ok	ok/ko ??
XPIC - MIMO 2x2							
TDD	8.0 GHz					ok	Ko
FDD	2 X 4.0 GHz					ok	Ko
fFDD	2 X 4.0 GHz					ok	ok/ko ??
FD	4.0 GHz					ok	ok
MIMO 4x4							
TDD	4.0 GHz					ok	ok
FDD	2 X 2.0 GHz					ok	ok/ko ??
fFDD	2 X 2.0 GHz					ok	ok
FD	2.0 GHz					ok	ok

feasibility of four different schemes, namely Time Division Duplexer (TDD), Frequency Division Duplexing (FDD), flexible FDD (fFDD) and Full Duplex (FD) is evaluated. 256-QAM is considered as the maximum feasible modulation scheme. For each radio link architecture and scheme, the required channel or channels bandwidth is given in the second column.

The column labeled ‘Single connection feasibility’ in Table I considers that a single bi-directional link connection is feasible (‘ok’) when it is possible to allocate the channel or channels with the required bandwidth within the portions of the D-band spectrum available according to the regulation. When this is not possible, it is marked as ‘ko’. The column labeled ‘Node feasibility’ considers that a node is feasible from the radio point of view if at least three different bi-directional link connection using non-overlapping channels can be implemented.

The solution based on the cross polar canceller (XPIC) or LoS-MIMO 2×2 technology, employing FD scheme, seems to be able to meet the capacity requirement. However, implementation of a FD approach using such a large bandwidth and in D-Band posses a lot of challenges to achieve the required isolation between TX and RX. Therefore, it is considered that the baseline solution should be based on D-Band transceivers using 2-GHz channels and able to handle modulation orders up to 256-QAM. With this kind of transceiver, different levels of capacities can be explored and it enables the use of a fFDD to achieve the 100 Gbit/s capacity.

B. *Propagation Constraints*

In order to be able to define the transceiver specifications, we need the required Gross System Gain (GSG) for given propagation conditions and availability. In the study presented in [6], it was assumed that a rain rate of more than 60 mm/h would never be statistically exceeded in Europe for more than 0,01 % of a year.

Fig.1 shows the relation between the required GSG and the hop length considering a rain rate of 60 mm/h. The plot is obtained following the methodology in [14]. The red lines correspond to the case of 99.999 % of availability (the most demanding), the blue lines to 99.99 % of availability and the magenta lines to 99.9 % of availability. The continuous lines are for a center frequency of 130 GHz and the dotted lines are for a center frequency of 170 GHz. The difference in required GSG between the two extremes of the D-Band remains below 3 dBs.

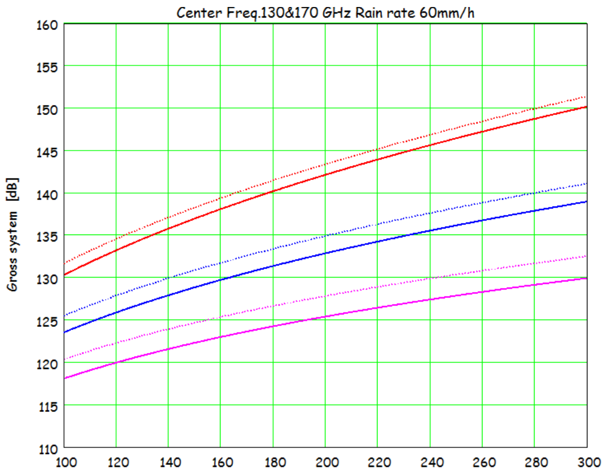

Fig. 1. Gross System Gain and hop length in different conditions.

III. PROPOSED ARCHITECTURE

Bearing in mind the constraints in section II, the transceiver architecture in Fig. 2 has been proposed [6]. The transceiver has the following features:

- Two completely different chains for TX and RX, including the antennas.
- For both TX and RX, a square (nxn) phased array antenna. Each element of the TX antenna is fed by its own TX chain, made of a power-amplifier (PA) directly connected

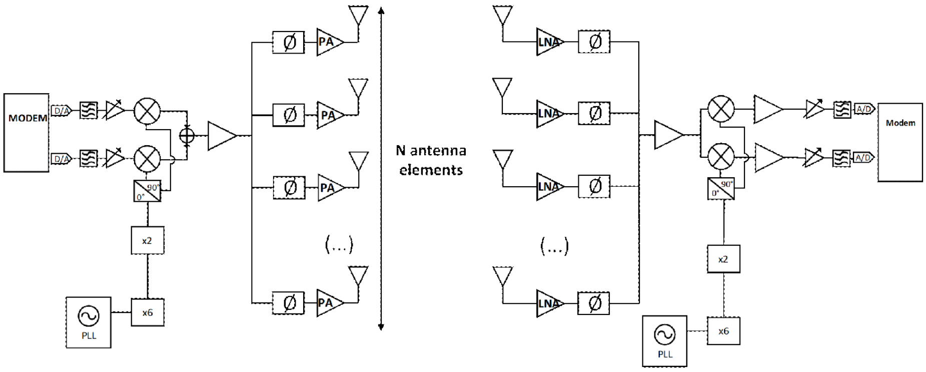

Fig. 2. Block diagram of the proposed architecture for the D-Band phased array transceiver.

to the antenna element and a phase shifter preceding the PA. Similarly, each element of the RX antenna feeds its own RX chain, composed of a low-noise amplifier (LNA) and a phase shifter.

- All Tx Chains are fed by a D-Band upconverter.
- All RX Chains contributions are summed coherently at the input of a D-Band downconverter
- Up and down converters are connected to a Base-band circuitry that includes Mod/Dem functionalities.

Fig. 3 explores the potential use cases of the proposed D-Band transceiver when employed in a LoS-MIMO 4×4 radio solution. The figure shows the estimated hop-lengths that could be achieved for different antenna sizes and modulation schemes. As it can be observed, different use cases can be addressed, with capacity levels up to 100 Gbps and hop lengths exceeding 1 km.

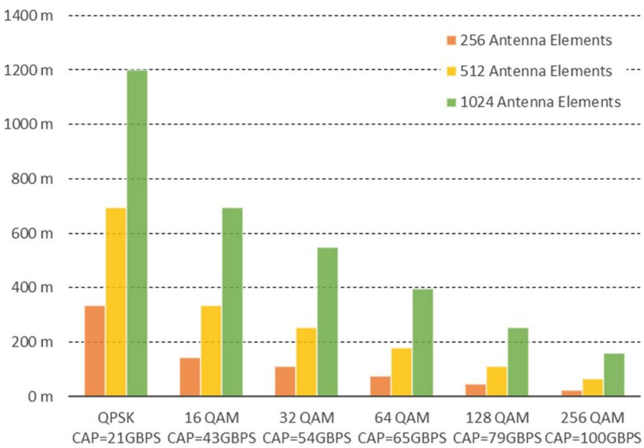

Fig. 3. D-band link performance depending on size of an antenna array and modulation for 2 GHz channel.

IV. Technology Choices

The technologies described in the following subsections are being investigated for the physical implementation of the D-Band radio link.

A. Antenna Array

To prove the link concept, a scaled 16 sub-set of an antenna array is proposed for demonstration. The planned implementation of D-band antenna array with a set of 4-channel monolithic microwave integrated circuits (MMIC) is shown in Fig. 4. The phased antenna array consists of antenna elements arranged into a half-wavelength (1.0 mm) grid and four channel MMIC core chips. The core chips must fit into the array spacing which sets a practical MMIC size limit of 1.5 × 1.5 mm^2. All RF and DC interconnects must fit into the spacing between the chips. The targeted operating frequency range for the phased antenna array is 140–160 GHz.

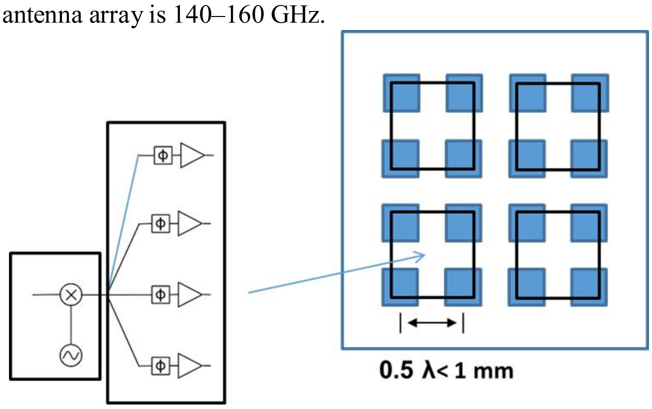

Fig. 4. Planned D-band phased antenna array (filled squares) geometry with 4-channel MMIC core chips (squares).

The aperture-coupled patch antenna is chosen as an array element (see Fig. 5).

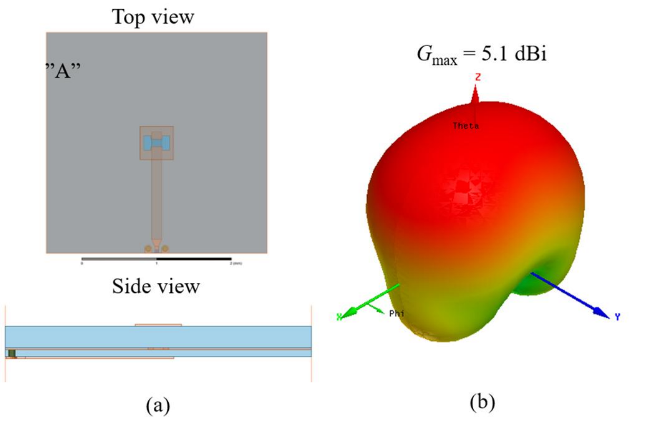

Fig. 5. Patch antenna for D-band phased array. (a) geometry, (b) simulated gain pattern.

The presented D-band antennas and PCB substrate technology based on Astra MT-77 substrate material show promising performance. It enables the future integration of MMICs and antennas into scalable phased antenna arrays. We have estimated to be able to reach a GSG around 135 dB when considering 256 element antenna and QPSK in the 2-GHz channel.

B. MMIC Technology

ST Microelectronics 55 nm SiGe BiCMOS technology is utilized for design and fabrication of MMICs of the link. As demonstration of the technology, experimental results for a D-band high-gain amplifier is presented here. The design of MMICs for the link is addressing two key challenges: design of wideband circuits at frequencies, where the transistor gain is limited by the parasitic elements and the maximum frequency of the active components, and design of compact circuits to fit dimensions of the antenna array.

The amplifier is based on three cascaded single-ended amplifiers matched to 50 Ohm (see Fig. 6). The amplifier achieves the maximum gain of 25 dB at 150 GHz and a Small-Signal gain (SS-Gain) > 18 dB over the full D-band (130 to 175 GHz) with an output power at 1 dB compression point (OP1dB) and a saturated output power (Psat) greater than -3 dBm and 2 dBm respectively (see Fig. 7). It consumes 50 mA from a 2.5 V power supply. The size of the amplifier (without probing pads) is only 0.27 x 0.18 mm² or less than 0.05 mm².

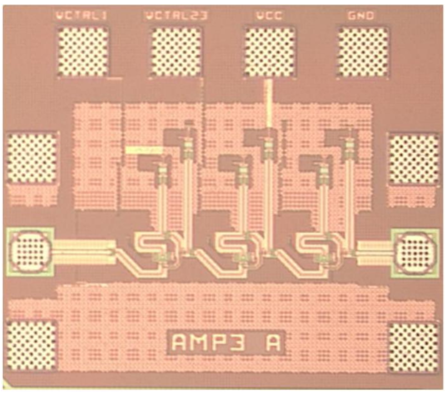

Fig. 6. Photo of the high-gain D-band amplifier.

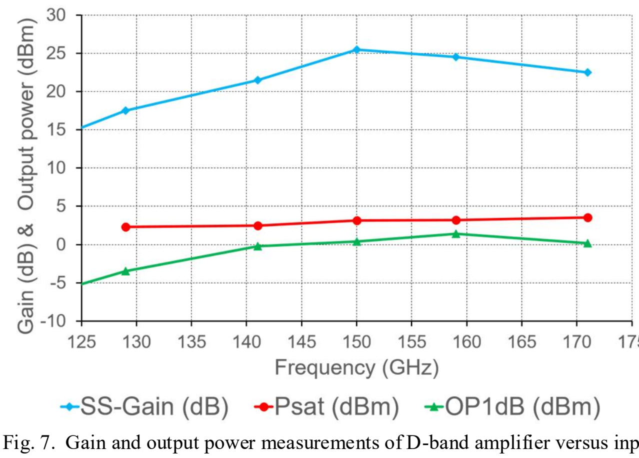

Fig. 7. Gain and output power measurements of D-band amplifier versus input frequency.

Figure 8 shows the output power of the D-band amplifier versus input power. There is a good agreement between simulations and on-wafer measurements, which demonstrates that the models of the design kit are very accurate up to the D-band and that the back end of line (BEOL) is well defined to perform both accurate parasitic extraction and accurate electromagnetic simulation (EM). Realization of this very compact circuit with good performances and very close to simulations demonstrates applicability of selected 55 nm SiGe BiCMOS process for the design of MMICs of the D- band transmitter.

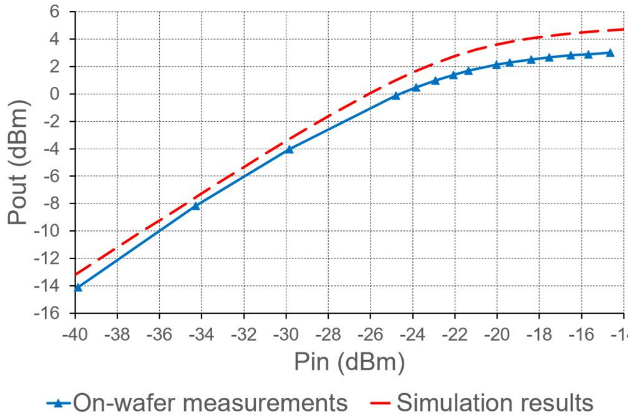

Fig. 8. Output power of D-band amplifier versus input power at 150 GHz.

C. Integration Technology

Advanced printed circuit board (PCB) technology was chosen as the integration platform. Required line widths and gaps down to 50 um can be reached by using mSAP (semi-additive processing) on outer copper layers. HDI-anylayer (high density interconnect) construction technology is used to have minimum size (down to 80 um) laser vias between PCB metal layers. A thin (<25 um) solder mask layer is needed in order to support flip-chip reflowing of MMICs.

The MMIC chips are processed in a multiproject wafer and are available only as separated dies. However, solder bumps can be processed on these too with specialized equipment using solder jetting and laser reflow. A solder ball size of 40 um was chosen for the D-band application. The solder alloy is SAC305. Prior to adding the solder balls the aluminium contact pads on the dies must be gold-plated which is a separate process step.

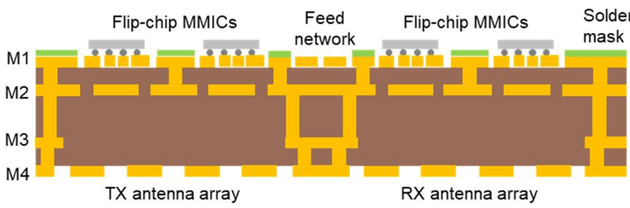

Fig. 9. Proposed physical implementation of the array.

The solder bumped MMICs are assembled on the integration platform using standard reflow processing. The thin solder mask around the PCB contact pads prevents the solder from flowing along copper tracks. A possible physical implementation of the phased antenna array is shown in Fig. 9.

V. CONCLUSIONS

This paper reviews the constraints defining a possible transceiver architecture that can be used as a base line to provide radio connection for a meshed transport network for 5G and beyond. The proposed transceiver architecture is a scalable solution, in terms of capacity and channel width, fulfilling the most demanding cases.

The paper presents the studies of technologies needed to implement the base-line transceiver. D-band antennas and PCB substrate technology based on advanced substrate material show promising performance for the integration with MMICs into scalable phased antenna arrays. MMICs design in D-band presents a big challenge due to the space constraints to fit in the antenna array and the limited transistor gain. However, realization of a very compact high-gain amplifier with good performances very closed to simulations demonstrates applicability of selected 55 nm SiGe BiCMOS process for the design of the D-band transmitter MMICs.

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