PROJECT FINAL REPORT

Grant Agreement number: 619563

Project acronym: MIWAVES

Project title: Beyond 2020 Heterogeneous Wireless Network with Millimeter-Wave Small-Cell Access and Backhauling

Funding Scheme: IP

Period covered: from January 2015 to April 2017

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1 List of partners

Partner name	Partner Type	Short Name	Country
COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES CEA (Coordinator)	Research Institute	CEA	FRANCE
TELECOM ITALIA SPA	Large Company	Telecom Italia	ITALY
ORANGE SA	Large Company	Orange	FRANCE
NOKIA SOLUTIONS AND NETWORKS OY	Large Company	Nokia	FINLAND
INTEL DEUTSCHLAND GMBH	Large Company	Intel	GERMANY
STMICROELECTRONICS S.A.	Large Company	ST-Fr	FRANCE
NATIONAL INSTRUMENTS DRESDEN GMBH	Large Company	NI	GERMANY
SIVERS IMA AKTIEBOLAG	SME	Sivers	SWEDEN
OPTIPRINT AG	SME	Optiprint	SWITZERLAND
Teknologian tutkimuskeskus VTT Oy	Research Institute	VTT	FINLAND
TECHNISCHE UNIVERSITAET DRESDEN	University	TUD	GERMANY
TECNOLOGIAS SERVICIOS TELEMATICOS Y SISTEMAS S.A	SME	TST	SPAIN
UNIVERSITE DE RENNES I	University	UR1	FRANCE
UNIVERSITY OF SURREY	University	University of Surrey	UNITED KINGDOM
STMICROELECTRONICS SR	Large Company	ST-I	ITALY

2 Executive summary

Future 5G radio systems will have to face the ever increasing mobile broadband traffic (eMBB: enhanced Mobile BroadBand 5G use case) mostly driven by video streaming applications on smartphones and tablets. However, the classical spectrum below 6 GHz will soon be saturated, leading to huge interference management issues either in licensed or unlicensed bands. Hence the use of new frequency bands in the millimeter-wave spectrum will be a necessity. Due to the high path loss at these frequencies, their use can only be viable for small cells. Connecting these small cells to the core network may necessitate the use of wireless backhaul (BH) links, since connection by an optical fibre is often difficult and costly. For the same reasons of spectrum saturation below 6GHz, millimetric waves (mmW) are also to be envisaged in this case.

MiWaveS aimed to develop the key technologies for the implementation of mmW wireless access and backhaul in heterogeneous networks (Figure 1). Installed in dense urban environments, miniature mmW small-cell access-points (AP) connected to the cellular network through optical fibre or mmW wireless BH should support massive data exchanges for mobile users with low latency, low interferences, high QoS and low power consumption per bit.

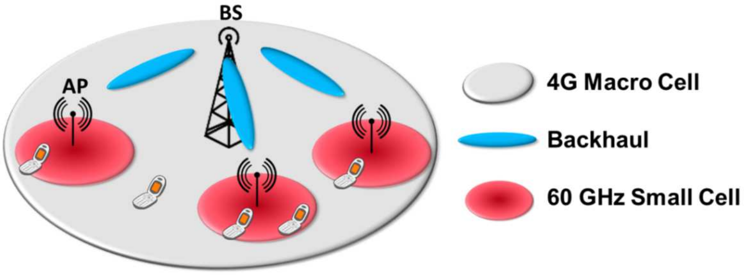


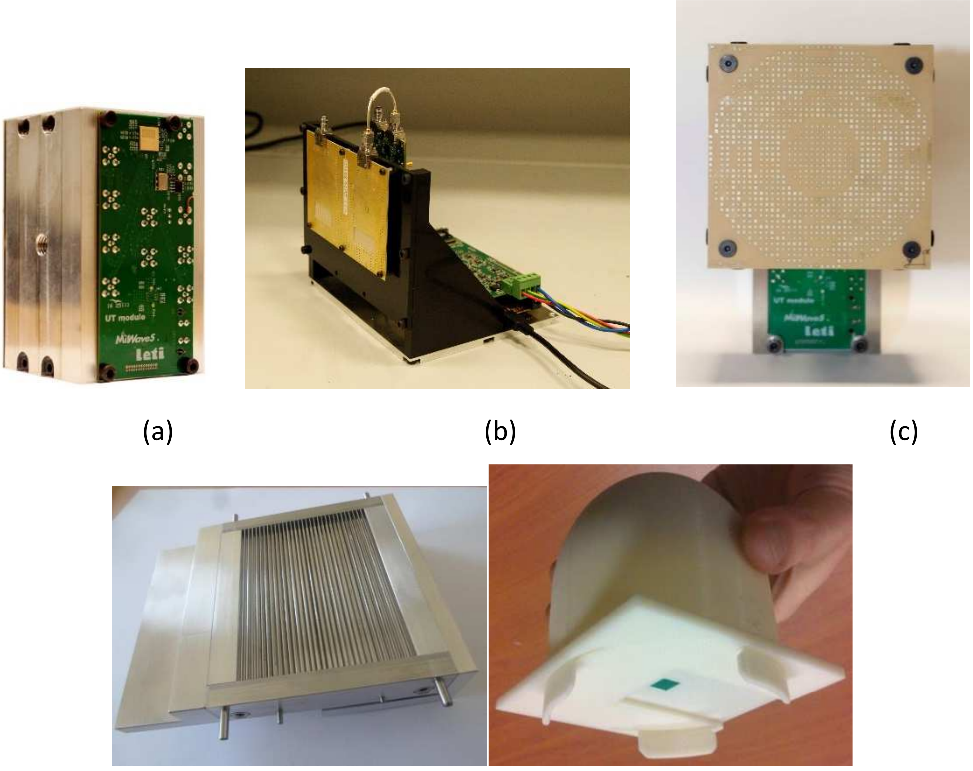
Figure 1 HetNet with mmW small-cells.

MiWaveS proposed new key technology enablers in the mmW domain, more precisely in V band (57–66 GHz) for access, and E (71-86 GHz) and V band for BH. The most significant challenges arise from the higher path loss occurring at mmW than at legacy frequencies (0.7–6 GHz). Therefore, MiWaveS first activity was to define use cases, calculate link budgets and define **Key Performance Indicators (KPIs) in terms of coverage and throughput**. From this study, it became clear that high-gain antennas with smart beam-steering/beam-switching capability were needed, both for radio access and BH, to cope with coverage and QoS requirements. MiWaves then designed smart deployment algorithms, e.g. for fast and robust beam alignment/tracking, and developed transceivers and antennas to cope with the above mentioned requirements. Regarding the V-band access link hardware developments, it was decided that due to power consumption, cost and integration constraints, only AP would be designed with beamsteering/switching antennas (though for beam alignment demonstrations, beam switching off-the-shelf antennas devices were used at both ends).

For *user* equipments, the goal was to minimize power consumption, size and cost by closely integrating the antenna (with no beamforming) and the radio transceiver in a single packaged module, that was based on organic materials (Figure 2a). At AP level, several beam-steering/beam-switching antenna array schemes were investigated based on Rotman-lens beamformers (Figure 2b), continuous transverse stub (CTS antennas), and phased arrays. Due to the high gain requested to cover the large distances between two BH nodes (up to 200m), it was found necessary to use a lens antenna. The lens can be low cost (3D printed plastic lens (Figure 2e), or a planar electronic transmitarray (Figure 2c), where for fixed-beam operation, the user device box was used as the focal source of the V band BH lens antennas. An alternative solution for beamsteering BH antenna is a broadband CTS antenna, developed at E-band (Figure 2d)

Finally, a subset of these components was integrated with a real time digital base band developed in MiWaveS and tested in indoor *and* outdoor field trials that illustrate the most important use cases and validate the main KPIs.

It should be noted that mmW transmissions also contribute to a reduced exposure of the public to electromagnetic field thanks to lower transmitted power and reduced skin penetration at mmW, steerable directive antennas focusing the signals in the directions of interest, and offloading data traffic from the sub-6 GHz legacy base-stations.



(a) (b) (c)

(d) (e)

Figure 2: Examples of fabricated antenna prototypes: a) user terminal b) V-band Access Point: Rotman lens with transmit and receive 32 element antenna arrays c) Discrete lens with user terminal transceiver d) E-band broadband CTS antenna e) V-band dielectric lens with focal feed antenna

3 Context

An unprecedented growth of the global mobile-data traffic is forecasted in the coming years, mostly driven by video streaming applications and cloud computing on smartphones and tablets.

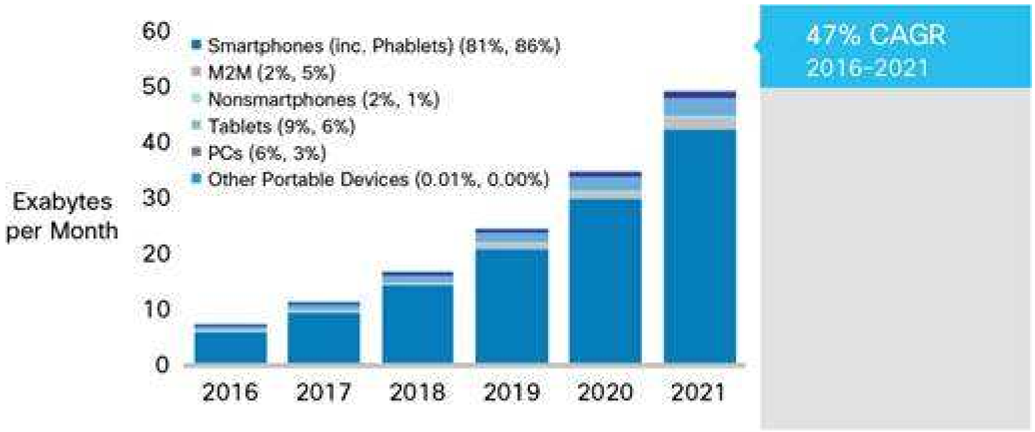


Figure 3: Global mobile data growth by device type (in exabytes per month). Source: Cisco VNI mobile 2017*

The 4G+ LTE-A network will provide higher bit rate per user, but will absorb only part of this traffic in the middle term. It is complemented by the deployment of Wi-Fi access points and small cells in dense urban areas, intended to offload a great part of the mobile data traffic. However, the spectrum used by legacy radio access technologies (WiFi, LTE, etc.) below 6 GHz will soon be saturated, leading to huge interference management issues either in licensed or unlicensed bands. Another issue arises from the need for wireless backhaul links to connect small cells to the core network since small cells are installed in places where an optical fibre may be difficult and costly to install and a wireless backbone still aggravates the spectrum load as it aggregates small cells access traffic. The ubiquity of access points may also drastically increase the exposure to electromagnetic fields (EMF), which could raise significant concerns within the urban population. In this context, the use of new frequency bands in the millimeter-wave spectrum will soon be mandatory to [1]fulfil the mobile traffic growth beyond 2020.

4 Key objectives

MiWaveS aims to contribute to the ongoing definition of the next generation (5G) of wireless mobile communication networks by developing the key technologies for the implementation of millimeter-wave (mmW) wireless access and backhaul in heterogeneous networks, taking advantage of the large spectrum resources available in the mmW range to enable a flexible spectrum usage as well as peak capacities above 10 Gbps aggregated throughput, well beyond the LTE-Advanced system. Installed in dense urban environments, miniature mmW small-cell access-points connected to the cellular network through optical fibre or mmW wireless backhaul will support massive data exchanges for mobile users with low latency, low interferences, high QoS and low power consumption per bit (Figure 1). They will also contribute to a reduced exposure of the public to EMF thanks to lower transmitted power and reduced skin penetration at mmW, steerable directive antennas focusing the signals in the directions of interest, and reduced data traffic through the sub-6 GHz legacy base-stations.

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[1] CAGR : Compound Annual Growth Rate

The key objectives of the project are:

- **Objective 1**: **Provide mobile access to content-rich data using a fast and broadband link**, which faces the challenge of bringing mmW radios to both the access points and the user terminals in order to exploit the large bandwidth available. The goal is to enable mobile radio access with up to 5 Gbps peak data rate and 250 Mbps of typical data rate per user (a factor x25 compared to LTE) and above 10 Gbps of aggregate capacity for backhaul (a factor x100 compared to LTE) using mmW radio technologies

- **Objective 2**: **to reduce the overall network EMF density (blue radio)**. Implementation of the 60 GHz access technology should allow reducing the overall exposure of users to microwave EMF in terms of the specific absorption rate. This can be achieved by separating the signaling traffic (sub 6GHz microwave standard, e.g. LTE) and data traffic (mmW 60 GHz band) as proposed in MiWaveS, thereby significantly reducing the EMF emissions in microwave bands. Considering that the signalling traffic represents about 30-40% of the total frame for an up-link LTE signal, a maximum reduction of 60-70% of the average power radiated by a mobile terminal in the microwave band can be envisioned theoretically when transmitting large amounts of data. In practice, the capacity of the up-link is not fully used, so that this reduction can be significantly lower.

In MiWaveS, the exposure to microwaves will be assessed in specific use cases based on some partners' expertise in cellular networks and results obtained from other projects. The mmW exposure will be accurately assessed for a worst-case scenario to ensure that expected exposure levels do not exceed exposure limits, defined today in terms of incident power density.

Both uplink and downlink are considered:

  - in uplink, to study and analyse exposure levels (in terms of SAR) induced in the most exposed parts of human body under representative use cases for the 60-GHz band, via dosimetric data measurements.
  - in down-link, the relationship between the required received power levels for different and scalable QoS services, associated with desired radio coverage values, and the corresponding electric field intensity values needs to be compared with exposure limit levels.

One success factor would be to show a decrease in the average exposure levels (in terms of SAR) between standard microwave networks and a heterogeneous architecture with the proposed mmW access link by at least 20% in specific use cases.

- **Objective 3**: **to reduce the power consumption of the radio access and backhaul links (green radio).** The use of mmW radios and directive antennas in short distance links (user access and small cell backhaul) results in a reduced emitted power requirement, more efficient transmitter implementation and a better efficiency of the spectrum usage (higher order modulations with large spectral efficiency can be used due to the more favorable link budget and lower interferences). The project targets to reduce significantly the radios and network power consumption by using mmW in comparison with existing solutions using lower frequency bands. Thus the deployment of the mmW small cells shall relax also the power consumption of both the cellular base stations and mobile devices.

  The project target is to provide a reduction by a factor of 100 of the energy per bit in nJ/bit for the access link and a factor of 10 for the back-haul link.

- **Objective 4: to increase the flexibility and the QoS of operator networks.** The mmW access points can route data hungry application traffic to fibre network available close to the small cell access point, whereas control and signalling of the network access can be handled by the conventional cellular network. By splitting the data and signalling traffics between the mmW and the 3G/4G sections of the network, **a larger flexibility and robustness can be obtained.** This will allow the operators to free some capacity from the conventional cellular network and **increase the QoS** for priority traffic (such as voice or other high-added value mobile services).

More precisely, this objective will be addressed mainly by the work performed on effective MAC layer protocols for small-cell access networks that will contribute to the provision of QoS for network users and flexibility of resource utilization for network operators, and the development of self-organising network algorithms providing QoS support in terms of packet delivery ratio and end-to-end delay over backhaul mmW networks. In addition, automatic beam-steering antennas will contribute to reduce the network operational cost and improve its flexibility. The feasibility of these performance improvements in an actual transmission system with implemented MAC and PHY will be tested in selected scenarios.

Security and robustness of the network can be improved with the approach proposed in MiWaveS thanks to the directive link between mobile devices and access point and the high atmospheric attenuation at 60-GHz frequency, which limit interferences between devices and guarantee the security of the transferred information.

MiWaveS plans to successfully demonstrate a typical use case based on the technologies developed in the project, taking into account realistic conditions (distances, environment. Final measurements shall provide a quantitative and qualitative assessment of flexibility, robustness and QoS obtained.

Fulfilling these objectives raises the following major technical challenges:

TC1. The first challenge is **the integration of low power mmW chipset in mobile** phone and tablets, whose performance allows the transmission of high data rate beyond 10 meters. The early power consumption of 60-GHz WiGig products (RF+Digital) achieving 2 Gbps at 5 meter range is typically above 1 W, which is manageable in tablets and laptops, but much too large for an intensive use by smartphones. Indeed, a reduction of the consumed power at least by 4 is required to be compatible with the energy stored in these mobile devices. This can be achieved by a close integration of the antennas with the mmW transceiver to minimize interconnection losses, by innovative architectures of transceivers and mixed-signal processing, and by an optimization of the chipset design.

TC2. The second technical challenge is to **raise the performance of mmW CMOS or BiCMOS chipsets to the requirements of backhauling applications**, while lowering their cost for the massive deployment of small cells in urban environments. Indeed, the current bandwidths covered by existing products in E-band and at 60 GHz are respectively 250 MHz to 1000 MHz (1.2%), and 1760 MHz (3%), while the expected backhauling solution could require up to 15% bandwidth (9/10 GHz).

Parallel architectures for analog and digital processing will become necessary to process such bandwidths, which triggers design and implementation issues.

TC3. The third technical challenge is the **design of the mmW access point**, which should link multiple users to the network. This access point should cover many channels at the same time over the 9- GHz frequency band (57-66 GHz), and manage the near/far dynamics. Depending on the multi-user access strategy considered (TDMA, FDMA, CDMA or SDMA), design constraints will be shifted from the transceiver to the digital modem or antennas.

TC4. At the global network level, the fourth technical challenge is **the fast and optimized relaying of information** (data routing), by a cross-layer optimization of the heterogeneous network.

TC5. The fifth challenge is the design of **multi-beams and steerable planar antennas** for access points and backhauling, where real breakthroughs are necessary to achieve efficient and cost-effective solutions, while reducing the human body exposure to EMF. The strategy and algorithms for beam steering or beam switching should be enclosed within the cross-layer optimization of the network.

5 Introduction

5G radio systems will have to face the ever increasing mobile broadband traffic mostly driven by video streaming applications on smartphones and tablets. However, the classical spectrum below 6 GHz will soon be saturated, leading to huge interference management issues both in licensed and unlicensed bands. Hence the introduction of new frequency bands in the millimeter-wave (mmW) range emerges as an interesting solution for spectrum scarcity. The MiWaveS vision of 5G systems is thus that of heterogeneous networks (HetNet) composed of mmW small cells with high data rate access points (APs) linked together with mmW wireless backhaul (BH).

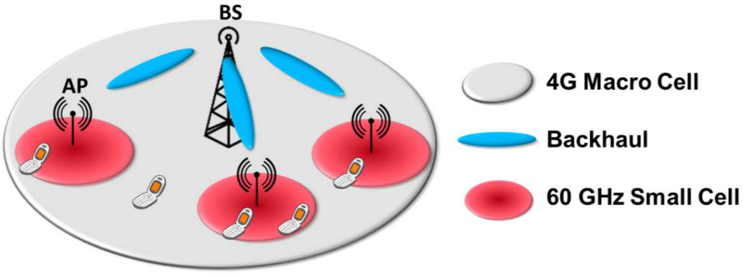

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Figure 4 MiWaveS' vision: HetNet with mmW small-cells

However, mmW access also comes with some significant challenges mainly arising from the higher path loss occurring at mmW and the lack of maturity of mmW component technology. (which for MiWaveS' focus are meant to be V band (57–66 GHz) for access, and either E (71-86 GHz) or V band for backhaul) than at legacy frequencies (0.7–6 GHz). This is why the first activity of MiWaveS was to define use cases and Key Performance Indicators (KPIs) for the set of considered frequency bands (Section 6). Based on link budgets calculations, it was shown that parameters such as antenna gain, modulation, EIRP and cell size, could be tuned so as to fit the use cases requirements. From this study, it became clear that high-gain antennas with smart beam-steering/beam-switching capability were needed, both for radio access and BH, to cope with the coverage and quality of service (QoS) requirements.

MiWaveS focussed on defining the network topologies, networking functions and algorithms involved in the operation of HetNet with mmW access and BH links (Section 7), and developing the transceivers and antennas required in their implementation (Section 8 and 9). A special attention was given to the issue of Electromagnetic Field Exposure (EMF) at mmW frequencies (Section 10). Lastly, proof-of-concepts were designed and developed, illustrating key technology components relevant to the most important use cases and validating the main KPIs (Section 11).

6 Scenarios, Use cases and System specifications

6.1 Use cases

In order to base the research activities of MiWaveS on solid foundations, five use cases were devised and refined, relevant for mmW HetNet systems:

1. Urban street-level outdoor mobile access and backhaul system, in which 1000-times higher spatial data consumption is expected by 2020. Users expect to have multi-Gigabit low-latency connections to services almost anywhere,

2. Large public events, covering massive crowd gatherings, sports events or vacation resorts. A great amount of users using data-hungry applications are served by the network, but just in some specific periods and in small areas,
3. Indoor wireless networking and coverage from outdoor, including the increase of indoor networks capacity and versatility, using indoor or outdoor antennas, and connecting to the operator network by quasi-fixed links,
4. Rural detached small-cell zones and villages, using mmW wireless BH technologies standalone or combined with wired line connection, to overcome the deployment difficulties of wireline BH installations,
5. Hotspot in shopping malls, considering ad-hoc deployment of small cells and mmW BH as a cost efficient solution to enable high data rate services inside the malls.

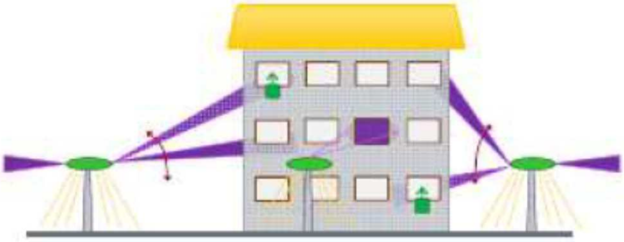

Figure 5: Indoor wireless networking and coverage from outdoor (use case 3).

6.2 System specifications

These defined use cases are key to illustrate MiWaveS vision of the future needs for high data rate and high capacity mobile networks. Each use case was characterized by defining assumptions (user data rate, connection density, traffic density), key technical challenges addressed KPIs and metrics used to evaluate the proposed solutions. KPIs included energy efficiency, end user capacity, reliability, area throughput, operational costs and QoS. Most important KPIs are summarized in the following table[2]

	BH channel	BH/ AP antenna	Link distances [meters]		Capacity [Gbit/s]	
			AP	BH	AP UL/DL	BH
1. Urban street-canyon	O-LOS, LOS	Small	25 – 50	50 – 200	2 / 5	5…10
2. Massive events	O-LOS, LOS	Large, small	25 – 100	50 – 400	2 / 2	3…10
3. Indoor from outdoors	Non-LOS	Small, large	10 – 20	20 – 100	(2 / 5)	5…10
4. Rural zones	LOS, O-LOS	Large	25 – 100	100 – 2000	2 / 5	2…10
5. Hotspot malls	Non-LOS O-LOS	Small	20 – 50	50 – 100	1 / 2	2…5

More detailed radio system characterizations and link budget calculations revealed the performance of needed technology components to achieve targeted capacities and distances in radio system level.

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[2] LOS= Line of Sight, O-LOS= Obstructed LOS, AP= Access Point,UL= UpLink, DL=DownLink

It became clear that high antenna gains were mandatory to compensate the high path loss at mmW frequencies.

Several deployment examples were provided to demonstrate the network dimensioning. It is obvious that in dense ultra-high capacity small cell network also efficient backhaul network is essential to provide enough capacity per square-kilometer. Network dimensioning was obtained in terms of antenna gain, bandwidth, modulation, EIRP constraints, cell size (for access), range for BH, and restricted number of BH hops limits wrt latency constraints. It was shown that the proposed generic HetNet structure can support all the use cases.

It is important to note that due to cost, complexity, power consumption and form factors, it was decided to have single antenna user terminals/equipments (UEs), leaving the high gain adaptive antennas on the AP side (however, for beam alignment demonstrations, off-the-shelf beam switching antennas devices were used at both ends) . Link budgets were calculated according to this assumption.

7 Radio resource management

The fact that mmW links are carried by beams requires new procedures for communication establishment, both at access and BH levels, as well as new radio resource management schemes (beam scheduling) .

- **LTE assisted communication establishment**
    - As a first step, the 3GPP LTE-A 2-phase relay node attachment procedure is extended to mmW APs, considered as relays, assuming an LTE Donor eNB coverage. The use of mobile broadband technology thus allows an initial access without having the small cell's mmW antenna directions adjusted a priori.
    - **Self-organized initial establishment procedure for a multi-hop inband mmW AP relay BH:** The proposed procedure reuses the existing 3GPP LTE relay initial attachment framework, on top of which the carrier aggregation technique is further employed to configure the mmW BH link as the secondary link. The proposed new mmW small cell discovery signals enable the mmW link detection and configuration. Moreover, it also facilitates the downlink beam alignment operation via the established RRC connection, i.e. multi-connected control channel. An LTE discovery procedure addressing the case where mmW APs can be turned ON/OFF (for energy saving) is adapted to that case, taking into account the beam directions of each AP, so that multi-hop BH is established in a self-organized fashion, together with beam alignment between successive APs. In addition, multiple mmW BH link configurations towards a single mmW small cell node furnishes the capability of dynamic BH routing.
    - **Access link:** assuming the UE is enabled with beamsteering/beamswitching capabilities, a macro-cell assisted random access method for the beam-steerable pencil-beam mmW UE is described. It is based on the existing LTE Physical Random Access Channel (PRACH) signal design. A multi-preamble PRACH signal (one per beam) is developed so that the AP should be able to determine and signal to the UE its preferred uplink beam for subsequent data transmission, thus achieving the uplink beamforming alignment.
- A **standalone** mmW **BH** was described as a system which builds up autonomously without macro-cell assistance. The proposed wireless mesh BH network solution provides self-organization, self-optimization and self-healing capabilities, by means of fast protection and restoration and QoS-aware congestion management with load balancing. Special focus is also on wireless link reliability and latency. In order to cope with link failures, fast re-routing on precomputed paths is operated (**dynamic routing).** The link schedule is determined by a network-wide semi-permanent configuration of a sequence of transmission sets of paths (**static scheduling).**
- **Radio Resource Management** (RRM) for HetNet mmW small cells was mathematically modeled as an optimization problem with some constraints. Here RRM means routing and link rate

scheduling. Different RRM algorithms for BH in mmW heterogeneous networks were then compared utilizing decomposition techniques. The main identified frameworks were **node-centric and path-centric,** and main pros and cons like complexity of hardware and computation were identified for each approach.

- **A joint beam-frequency multiuser scheduling** for mmW downlink system was developed. Two algorithms, the optimal one and a reduced complexity one, were developed. W.r.t. the latter, It was demonstrated that this computation efficient scheduling procedure with considerable reduced complexity can achieve the same target scheduling metric as the optimal algorithm. It was shown from simulation results that different UEs may be multiplexed in both frequency and beam domain, and that some UEs may be scheduled with multiple beams simultaneously.
- **Automatic antenna beamsteering and beamforming**A mmW radio link may be equipped with antenna arrays at both ends, or only at the AP if these arrays are deemed too complex for a UE, as it is the case in MiWaveS. In any case, beam alignment is the second step of the connection between two mmW nodes (after the random acces method in case of LTE-assisted access scheme). Therefore, if each node can form e.g. 16 different beams, in theory 16x16 possible beam combinations (exhaustive search) have to be tested, implying a lengthy procedure. Thus beam alignment algorithms for access links were proposed, to ease the implementation in systems suffering from hardware constraints.
  - **Black box algorithm**: based on iterative information exchanges between UE and AP; simulations showed that the proposed algorithm reduces computation complexity significantly from 256 evaluations in exhaustive search to 40 evaluations and 4 feedback, when the initiator and responder each have a uniform linear antenna array of 8 antennas and 16 beams.
  - **Gradient based algorithm**: due to implementation constraints, the black box algorithm was further simplified into a gradient based method. Simulations with realistic channel models showed that the two algorithms provide almost the same performance in tems of spectral efficiency.
  - A practical **RF codebook** was derived, based on genetic algorithm for analog and hybrid beamforming schemes where the antenna array is equipped with low-resolution phase shifters. The optimized codebook achieves a promising performance in this practical configuration. It is shown by simulations that simple 2-bit phase shifters provide acceptable performance for SNR over 40 dB reducing the hardware complexity. Furthermore, a low complexity channel estimation algorithm based on an enhanced one-sided search was proposed. This scheme has a high potential for demonstrator implementation. For simple BH channel with low number of multi-path components, analog beam-switching with limited steering range can be a viable option.
  - Lastly, the impact of three major types of impairments - phase noise, carrier frequency offset and IQ imbalance - were assessed with a link level simulator. For each one of those, compensation algorithms were proposed. Relaxed specifications were consequently drawn for the design of the RF hardware in the sequel of the project.

8 Radio technology for mmW access and backhauling

Radio Design Technology has a central role in the project as it provides the mmW radio transceivers needed to demonstrate the concepts and technologies developed in MiWaveS. According to the specification phase(Section 6.2), the main challenge involved in this task was to develop cost-effective highly-integrated solutions with low power consumption and a good power efficiency. Low-cost technologies are mandatory to address future 5G commercial applications and, in this respect, semiconductor technologies like CMOS and BiCMOS shall be utilized instead of more expensive technologies such as GaAs. The power consumption of the transceiver shall be significantly reduced as compared to existing chip-sets, this requirement being particularly true in the case of user terminal (e.g. smartphone, tablet) transceivers which shall not degrade the autonomy. Finally, the integration of the transceiver, and possibly the antennas, in a single chip or single module shall be targeted not only for size constraints but also to achieve higher energy efficiency and performance figures. In addition,

- in the case of **backhaul transceivers**, it is of paramount importance to ensure:
  - high output power to reach rather long distances up to a few hundreds of meters;
  - high linearity and very low phase noise to comply with high level modulation schemes required for very high data rates up to 10 Gbps.
- the **access point transceiver** shall operate across all sub-channels of the 57–66 GHz frequency band when collecting multiple user signals and should support antenna beam-steering capabilities. The receiver must handle a large dynamic range because of the large expected variations of the link budget (users near the AP or at the cell edge, LOS/NLOS conditions).
- As mentioned above, **for the user terminal**, the transceiver design shall focus on low power consumption, low-cost and high integration with the antenna.

In addition to the transceiver development, this activity also included mmW LTCC and LCP platforms development, manufactured by VTT and Optiprint, respectively. These platforms served both the transceiver and antenna developments and, whenever possible, a co-integration of the transceiver and antennas has been implemented. Several manufacturing runs took place during the project. The challenges exist both in material and manufacturing technologies as advanced highly-integrated mmW front-ends need complex and low-loss multilayer platforms.

8.1 Building blocks for 60 GHz backhaul radio, access point and user terminal

ST-Fr provided 65nm CMOS transceiver chips, co-developed with CEA-LETI. It was designed for WiGiG-like applications and is applicable to 5G wireless access and BH. The 60 GHz chip is based on the CO65RF technology from STMicroelectronics. It is a fully integrated circuit including transmitter, receiver and phase-locked loop (PLL) circuitry to cover the 4 IEEE channels defined between 57 and 66 GHz. The frequency generation of the local oscillator signals is common to the transmitter and receiver. The transceiver uses a double stage frequency conversion scheme with an IF frequency of 20 GHz. Baseband I&Q signals are available both for Rx and Tx. The transceiver chip is fabricated using a standard CMOS 65nm bulk technology. The chip size is 2.8*3.3 mm². Furthermore, a cost-effective BGA flip-chip module was designed to package the transceiver and allow its use on standard application printed circuit boards (PCBs). In the MiWaveS project, the 65 nm CMOS transceiver chip was utilized as the 60 GHz BH radio, user terminal radio but also as a building block in the phased array AP front-end module.

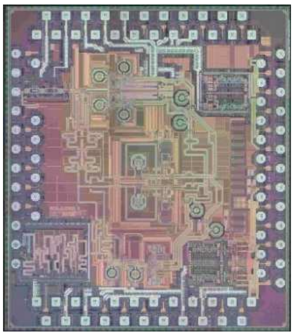


Figure 6**:** 60 GHz transceiver chip realized in 65 nm CMOS technology

Transceiver test boards were fabricated, assembled and tested for the user device and AP node.

User Device

In the case of the user device, Rx and Tx patch antennas are integrated on the transceiver interposer board.

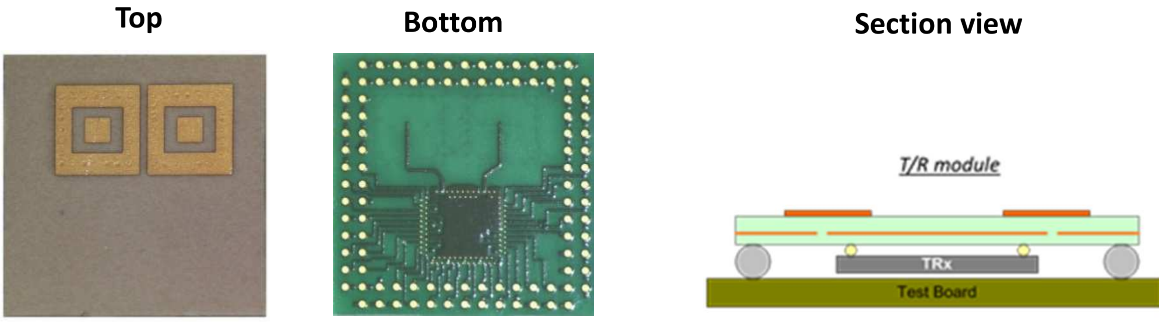


Figure 7 Integrated 60 GHz user device interposer board

The user terminal module was built on a LCP multi-layer substrate which size is 10×10 mm^2. The CO65RF transceiver chip was flip-chipped on the bottom side of the board. On the top side of the board, there are two separate linearly polarized fixed-beam aperture coupled patch antennas, one for reception and one for transmission. The LCP module is further flip-chipped on a larger test PCB for test and demonstration purposes. The interface between the module and PCB includes Rx and Tx baseband I/Q signals, digital control and transceiver supply voltage lines.

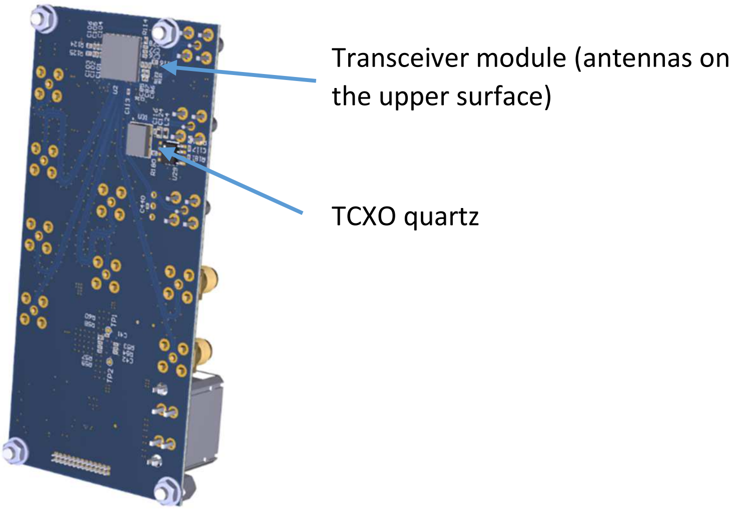


Figure 8 Illustration of the User Terminal PCB board (back side).

The power consumption of the user terminal transceiver was evaluated by simulation and the simulated power consumption was compared to the state-of-the-art: circuits that are able to cover medium to long distances have a consumption (Tx+Rx) of the order of 2 W, which is much too high for a UE. The cirduit dsigned here has a consumption of about 500mW.

Backhaul

Due to the high gain requested to cover the larger (than UE-AP) distances between two BH nodes (up to 200m), it was deemed necessary to use a lens antenna. The lens can be low cost (3D printed plastic lens) (Figure 13), or a planar reconfigurable electronic transmitarray (see section 9.3, Figure 13, Figure 14 and Figure 15). In the latter case, beams could be created by controlling numerically each element

of the lens. Nevertheless, at V-and E-band, the technology is not mature enough for such lenses; the solution is therefore to use a reconfigurable focal source array coupled with a passive lens.
For fixed-beam operation, the user device box can be also used as the focal source of the V band BH lens antennas (see section 5 for photo Figure 13 and lenses descriptions).

Access Point

In the case of the AP node, the above transceiver test board (Figure 8) was equipped with coaxial Rx and Tx connectors in order to connect with a switched beam Rotman lens antenna array (see Section 9.3 for Rotman lens description).

Another solution based on beamsteering arrays with phase shifters has also been studied. The phased array front-end includes the 60 GHz CMOS 65nm transceiver, a Tx/Rx duplex switch and four phase shifter chips, each composed of a PA, a Low Noise Amplifier (LNA), phase shifters and Tx/Rx switches. The transceiver and Single Pole Double Throw (SPDT) duplex switch are common to all antenna array elements, while separate phase-shifting MMICs are dedicated to each antenna element in order to decrease the design complexity and propose a solution that can be easily scaled to different phased array sizes.

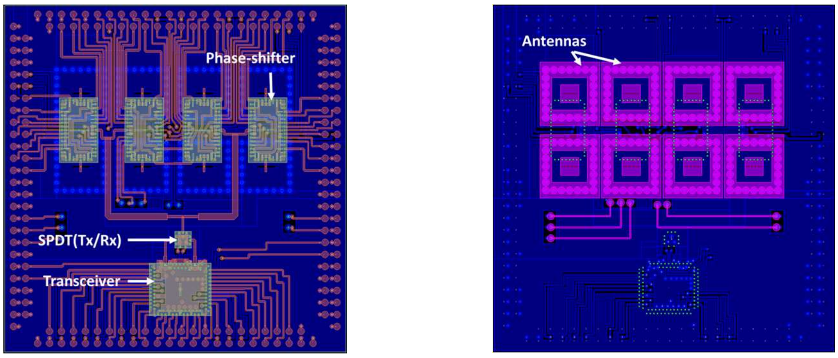


Figure 9: Bottom view (left) and top view (right) of the AP module layout composed of a 4x2 antenna array

Two phase shifters and related switch and amplifiers are integrated on a single chip to reduce the number of chips and to ease the signal routing on the interposer board.

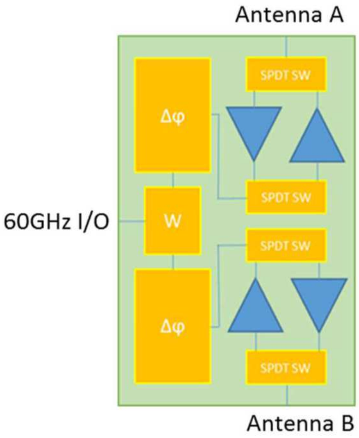


Figure 10 Active phase shifter front-end chip architecture.

An antenna array of 2x4 patch elements is used. The Tx/Rx duplex SPDT switch in 55-nm BiCMOS technology has been designed, fabricated and measured. The size of the SPDT switch chip is 0.9x0.9 mm^2. All the building blocks of this active integrated circuit have been designed and taped out. The size of this chip is 2.0x3.4 mm^2. A passive switched-type phase shifter is used in the chip. Two- and one-bit switched delay-line phase shifters are used in a series configuration to obtain a 3-bit phase shifter with a 45-degrees phase resolution. The switched delay line type phase shifter is rather large in size, has a significant loss and provides only a moderate phase shift resolution. To overcome these performance constraints, a vector modulator type phase shifter building block has also been designed, fabricated and characterized. Test measurements indicate that the vector modulator building block enables an accurate phase and gain control over the full V band. The LNA consists of three stages. The first stage uses a common source FET transistor and second and third stages a common emitter BJT transistor. The front-end is integrated on a LCP interposer board. The LCP module size is 19*19 mm^2 including the antenna array of 2*4 elements. The concept provides a compact scalable AP transceiver module that can be used in phased arrays of different sizes and meet various system level requirements.

The critical building blocks of the CMOS 65nm transceiver chip from the performance point of view are the LO synthesizer and PA. The phase noise of the current synthesizer allows the transmission of a 16QAM modulation but it has no performance margin to address 64QAM modulation. Unfortunately, this is a limitation of the used technology. Likewise, the transmitter output power is limited (Psat ~ 8.2-9.7 dBm at 1.8V nominal supply voltage depending on the used IEEE frequency channel). Therefore, it was decided to assess the performance of 28nm CMOS FD-SOI (Fully Depleted Silicon on Insulator) technology by designing, fabricating and testing a 60 GHz reconfigurable PA in 28 nm UTBB FD-SOI CMOS technology. The amplifier achieves an outstanding performance in terms of PAE (Power Added Efficiency, 21%), 1-dB compression point (18.2 dBm) and power consumption (74 mW). This latter building block was not meant to be integrated in the transceiver chipset.

8.2 Design, manufacture and test of building blocks for E- band backhaul radio

Sivers provided the E-band (71-76 GHz) transceiver module for the BH demonstration. The transceiver has been augmented by external Local Oscillator (LO) and Analog Front-end (AFE) boards. External LOs with on/off switching allow the transceiver use in the TDD operation scheme. The AFE board provides the required IF to baseband frequency conversion. In order to solve a problem related to the leakage of the PA broadband noise to the receiver input, a commercial SPDT duplex waveguide switch has been added to the transceiver waveguide Rx/Tx inputs.

In the course of the transceiver development, two performance parameters have been observed to be of key importance in BH radios. On the one hand, the transmitter shall provide a high output power with a good linearity. On the other hand, trend in millimetre-wave BH radios is towards multi-level modulation schemes such as 64 and 128 QAM in order to increase data rates. This sets strict constraints on the phase noise of the transceiver local oscillators. Therefore, in the project, special building block developments have been initiated both on power amplifiers and frequency synthesizers. Furthermore, a simulation study has been carried out on power amplifier topologies with a high efficiency.

8.2.1 Frequency Synthesizers

ST-Fr has developed an E-band frequency synthesizer in 55nm BiCMOS technology. The frequency synthesizer includes a single fractional PLL (Phase Locked Loop) and DCXO (Digitally-Compensated Crystal Oscillator) to comply with all V and E-band radio channel allocations. To avoid an external analog loop filter, this work proposes a digital control of the VCO. By this way, the loop filter is fully integrated, digitally reconfigurable and further integrates a VCO linearization to ensure optimal SNR despite voltage and temperature drifts. The digital control flexibility is a novelty for BH applications and empowers VCO control as it implements linearization. The 40 GHz VCO is followed by a frequency doubler in order to achieve the final E-band frequency. The test chip has been designed, fabricated and characterized.. The measured phase noise at 86 GHz at 1 MHz frequency offset is-97 dBc/Hz.

The 20GHz 55 nm BiCMOS VCO dice taped out by ST-I in December 2015 and received in July 2016 has been fully characterized. The VCO phase noise penalty (5dB) which was measured from the dice of the previous tape-out with respect to simulations, and was due to the tank-tail coupling, has been reduced to less than 1 dB. The 20GHz single core VCO and x4 multiplier achieves a phase noise less than -101 dBc/Hz at 1 MHz frequency offset at 76 GHz. The push-push x4 multiplier chain does not add any noise penalty to the 20GHz multi-core VCO phase noise. The 3 dB noise reduction, predicted by the multi-core VCO theory, has been well verified by the measurements. The minimum phase noise is -107 dBc/Hz at 1MHz offset in the frequency range from 71 to 76 GHz. **To our knowledge this is the lowest phase noise measured in the E-Band using integrated technologies and CMOS-compatible supplies**. A patent application has been filed on the new phase noise reconfigurable multi-core VCO architecture, while two conference papers have been presented and 1 journal paper has been accepted and published on the IEEE JSSC of July 2017.

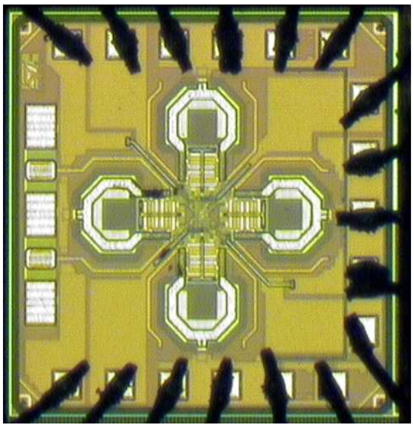


Figure 11 20 GHz multi-core VCO in 55 nm BiCMOS technology.

8.2.2 Power Amplifiers

ST-I has designed an E band 55nm BiCMOS power amplifier, which has been taped-out in December 2015, received from fabrication in July 2016 and fully measured and characterized. It is based on the patented in-line DDAT (Double Distributed Active Transformer) structure for the power splitting and combining. The measurements indicate an output power of more than 24 dBm at 66 GHz and 20 dBm at 71 GHz. The gain is 24 dB at 66 GHz, 20 dB at 71 GHz but drops to 11.6 dB at 76 GHz. The main performance discrepancy is the frequency shift of 17 GHz, due to an inaccurate extraction of layout parasitic effects. Nevertheless, the power gain and saturated output power are in line with the simulations. A state-of-the-art comparison on millimeter-wave PAs has been done, and it shows that the developed **in-line DDAT BiCMOS PA** provides the highest density **in terms of RF output power-to-silicon area consumption ratio**. A paper, describing the PA structure and characterization, has been prepared, submitted and accepted and will be soon published in the IEEE Microwave and Wireless Components Letters.

Concerning the E band BiCMOS high output power PA investigation activity, two patents have been filed, one related to the in-line DDAT power combining architecture and the other related to general DDAT based push-pull architecture concept.

Various modulation and coding schemes will be applied for mmW high data rate BH and access links. These signals do not have a constant amplitude envelope but involve large PAPRs (peak-to-average power ratio). The highest efficiency point of a power amplifier is usually close to the saturated power region. However, the linearity requirement requires the amplifier to be backed-off by several dBs from the saturated output power. The back-off will degrade considerably the amplifier efficiency. In order to circumvent the linearity-efficiency trade-off, it is necessary to control the load resistance or the DC bias voltage of the power amplifier. These dynamic linearization techniques have been widely investigated in literature at low GHz wireless frequencies. MiWaveS project has investigated the feasibility of these linearization techniques at mmW frequencies, where only a few studies have been reported so far. In particular, a balanced GaAs pHEMT power amplifier stage operating at E-band has been designed, and it has been used as a reference amplifier in the performance comparison. Doherty and Chireix out-phasing amplifiers have been selected to the performance comparison. These amplifier architectures show a high efficiency (PAE) at lower microwave frequencies. The performed simulations indicate that a Doherty amplifier gives a clear performance advantage compared to a balanced power amplifier configuration. In contrast, the Chireix out-phasing amplifier concept is not feasible for a millimetre-wave frequency operation

8.3 LTCC platforms for mmW front-ends

LTCC is a competitive integration technology for today’s mmW communication systems. In this project, LTCC technology from VTT was used to implement the designs from three MiWaveS partners (-UR1, IMC and VTT). Three LTCC manufacturing runs were carried out during the project. The first one included a passive 60-GHz prototype CTS antenna of UR1 and matching circuits of mmW SP3T and SP4T switches of VTT. The designs of these two partners were quite different. The design of VTT needed only 2 conductor layers on a single tape while UR1’s design required 18 tape layers. This latter design was very challenging from the manufacturing point of view, in particular for the accurate alignment of vias and conductors. Very successful results have been obtained. The second LTCC manufacturing run included several user-terminal patch antenna designs from IMC and modified SP3T and SP4T switch matching test structures from VTT. The patch antennas required air cavities to be used, which was the main fabrication challenge of this run. The third LTCC manufacturing run included an active 60-GHz switched beam CTS antenna array for an access point and was thereby a more advanced version compared to the passive CTS antenna of the run#1. The active inter-leaved 60-GHz CTS antenna array was designed by UR1 and the related beam-switching network by VTT and UR1 (depending on the antenna versions).

8.4 LCP platforms for mmW front-ends

It was recognised at the MiWaveS outset that accurate LCP dielectric properties were unavailable for V-band and E-band frequencies both in the public domain and from the developers and suppliers of LCP, most notably Rogers Corporation (and their Ultralam 3000 materials). In the first year of the project, VTT developed a test programme and a series of test-structures were fabricated by Optiprint (“run#1”). VTT tested the structures and the results were distributed among the project partners.

Optiprint provided technical assistance to SIV for their test-structures and chose a four-layer construction in Rogers Corporation Ultralam 3000 (LCP) material. The most economical way to make a four layer construction involves a single double-sided core clad with bond-ply (to form dielectric layers 1 & 3) along with Copper foil (to form conductor layers 1 & 4). In the PCB industry, this is known as a “foil-build” (as opposed to a “core-build” that sees two Copper-clad laminates bonded together with bond-ply). The feature-to-feature accuracy requirements between conductor layers 1 & 2 also favored this approach. This detail warrants to be mentioned because it is a construction not advised or supported by Rogers Corporation so there is a novel element to this work. Optiprint fabricated the SIV test-structures.

Six mmW PCB manufacturing runs were carried out in 2015. Most of the runs supported the antenna manufacturing. Run#5 supported also transceiver development. In run#5, an integrated user terminal module was fabricated which consists of Rx and Tx patch antennas and a 60-GHz CMOS transceiver.

Altogether 19 mmW PCB manufacturing runs were carried out during the project third period. Most of the runs (12 pcs) supported antenna manufacturing. Four runs included passive test structures and several amplifier designs in order to assess the feasibility of LCP technology for millimetre-wave modules. Three runs were made to realize the final integrated user device interposer boards. Moreover, Optiprint has investigated benefits of an additive etching process in order to further improve the accuracy.

During the project for instance the following designs have been fabricated:

- Planar V band BH antenna,
- Rotman lens antennas,
- Focal feeder board for discrete lens antennas,
- Discrete lens arrays,
- User terminal modules,
- Passive pillbox-based beam-forming networks.

In conclusion, LCP platforms were a key element in the project, and more generally an enabling technology for the mmW front-end and transceivers developments. Moreover, their construction led to innovative fabrication processes.

9 Antennas

The main principles which guided the choice for antennas were radiation performance (gain, radiation patterns, bandwidth, etc.), form factor, and cost. The antenna systems studied in MiWaveS have also been selected from system-level specifications (Section 6). These design activities relied on an intensive use of electromagnetic solvers and were supported, when needed and/or possible, by intermediate prototyping and experimental characterisations (S-parameters and radiation performance). All design activities account for the fabrication constraints of organic and LTCC integration platforms, as well as the specific materials used in each of these technologies, taking into account electrical performances, manufacturability and cost. The main results have been reported in Deliverable D4.5.

- On the **user terminal** side, for the sake of low cost and low complexity/consumption, a fixed single antenna element was chosen, leaving the path loss compensation to the access point side with higher gain antennas.

- For **access points**, due to user’s mobility, steerable antenna arrays was the recommended choice, allowing to steer/switch the antenna beam electronically towards the user. The beam orientation is obtained by phase shifting each antenna element. Three different phase shifting solutions are possible:

    - **Digital beamsteering**, where each antenna element is connected to an independent transceiver, causing this solution to be too costly and hence discarded by MiWaveS.
    - **Electronic beam steering**, where the phase of each antenna element is controlled in the analog domain, so that a single transceiver feeds the steered array.
    - **Electronic beam switching**, where the antenna array is fed through a passive beamformer (such as Rotman lens) and a switching matrix is used between the transceiver and the beamformer to select the appropriate beam. In this case also, a single transceiver is required.

- For **backhaul (BH) links**, the larger distances (up to 200m vs. 50m for access) require a different type of antennas in order to ensure a higher gain. In spite of the fact that at first sight there is no mobility of the BH ends, the masts on which they are installed may sway and thus cause mobility. In addition, at connection time, an initial beam alignment procedure has to be performed. Therefore, the solution should ideally combine a means to increase the gain, while enabling flexible beams to perform beam alignment and tracking. Three main solutions were selected (note that the first one has fixed beam, and that other antennas have been alos developped):
    - A V-band antenna array with dielectric lens (fixed beam),
    - A V-band antenna array with planar (discrete) lens (switched beams),
    - An E-band antenna array based on Continuous Transverse Stubs (CTS) (switched beams).

In all cases, one major concern is to reduce losses, due to e.g. connecting cables. Thus, solutions where RF and antennas are integrated are privileged.

9.1 User Terminal

- For the **user terminal**, two different in-package integrated V-band antennas have been studied.

    - The first one is based on a classical aperture-coupled patch antenna configuration implemented on a multi-layer organic technology (LCP platform). This technology is widely used today for the integration of electronic and sensor systems in a system-in-package approach for many applications, including consumer applications with volume manufacturing needs. A UT module based on organic substrates with integrated antennas and a flip-chipped transceiver has been designed. It complies both with the design rules of Optiprint related to PCB technologies and assembly constraints. The simulation results are very satisfactory, with a very good impedance matching (reflection coefficient below -12 dB) and a stable gain above 8.2 dBi obtained over the 57-66 GHz frequency band. The antenna prototypes, fabricated by Optiprint, have been measured and exhibit acceptable results, with a maximum measured gains of 7.3 dBi and 7.7 dBi for the Tx and Rx antennas, respectively. The assembly of the UT module (transceiver flip-chipped on the organic substrate) and the soldering of this module on the demonstration board were achieved successfully and allowed the user terminal demonstration (see WP5). It has also been used as a focal source of a discrete lens designed in V-band for the BH demonstration with a successful link offering 7 Gbps at 25 m and 3,5 Gbps at 70 m.

    - The second antenna design uses LTCC technology. Three different antenna structures have been designed and simulated. The first one is based on an air-cavity backed aperture-coupled patch antenna. The other two designs use a more sophisticated approach where two surface waves are excited out of phase to cancel out each other. In addition, ring-resonators were designed to obtain the attenuation constant and the effective dielectric constant of the used microstrip lines. All aforementioned designs have been manufactured by VTT on LTCC substrates and characterised experimentally (S-parameters, radiation), demonstrating very satisfactory results.

9.2 Access Point

Three complementary antennas for **APs** have been developed, based on different concepts with various challenges and risk levels.

- A Rotman lens (RL) beam-former with 5 beam ports and 8 antenna array ports has been designed on a multi-layer LCP substrate. The RL generates a set of phase-shifted replica of the signal at the antenna array ports. Depending on the excited input port, the phase shift between signals at antenna array ports is different. The phase states of the RL correspond to the states of a 3-bit phase shifter. The RL has been combined with 1x8, 2x8 and 4x8 aperture-coupled patch antenna arrays. The 8 array columns have been connected to the RL 8 array ports. In addition to the aperture-coupled patch element, similar arrays have been realized with a novel elliptical dipole element to fully exploit the beam-former bandwidth. For switched beam demonstrations the five beam port branches of the RL have been combined to a single antenna port by two TGS4305-FC SP3T switches. In order to compensate for the switch and beam-former losses active RL antennas have also been designed, manufactured and characterized. In the first active version a LNA has been inserted to antenna receive port and a PA to the antenna transmit port. A second active version includes a LNA in each receive beam port and a PA in each transmit beam port. By this means the loss of the SP3T switching network can be compensated. Moreover, a third active version, an active RL elliptical dipole antenna array with 8 LNAs and 8 PAs in the antenna array ports has been realized. This version compensates in addition to the switching network losses the loss of the RL beam-former and thereby its performance is comparable to the performance of a phased array antenna.

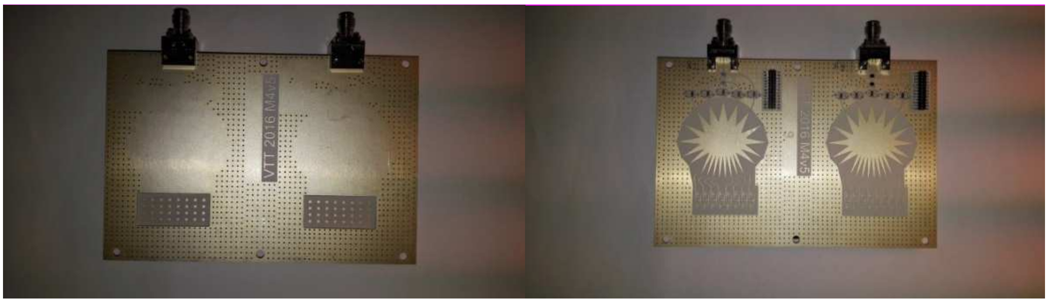


Figure 12 Active Rx and Tx patch antenna arrays with 32 elements (left) and the corresponding beam switching networks, 5 LNAs and PAs in RL beam ports, RL beam-formers and power combiner and divider networks (right).

- The second antenna under consideration is based on CTS concepts and on its integration in LTCC technology; this approach allows reaching a very broad bandwidth, at the expense of a complex antenna architecture. The antenna is fed by a beam switching quasi-optical pillbox coupler. The measurements showed very good antenna performance (26%-

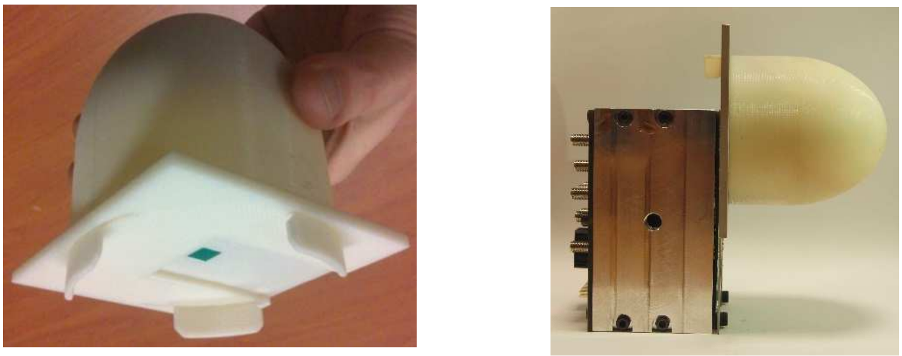
impedance bandwidth, peak gain of 14 dBi, stable radiation properties in the 50-66 GHz band). A LTCC switched-beam antenna for the AP was developed by UR1 and VTT, exploiting the split aperture decoupling technique. Two separate CTS antennas, designed to radiate two sets of interleaved beams, were co-integrated in an LTCC module with a switch network, comprising TGS4305-FC SP3T. Measurements confirmed that the antenna covers a ±38° scan range with high beam crossing levels (-3 dB) and low SLLs (<-20 dB for the broadside beam), in the 57-66 GHz band.

- Finally, the third antenna system is a phased array antenna. The module contains an RF transceiver IC, power splitters & combiners, TDD switches as well as phase-shifting and amplifying RFICs for beam-steering. The architecture and technology builds upon the developments of UT transceiver modules with integrated antennas (aperture coupled patch antenna) to manage risks and leverage development cost. This concept is modular and allows a flexible selection of the number of array elements. An antenna array containing eight elements (four in azimuth and two in elevation) has been designed. The 55-nm BiCMOS SPDT switch has been designed and taped out. The phase shifting modules have been fabricated. The first tests on building blocks of this module have demonstrated good performance. Unfortunately, the complete chip was not functional. However, the simulation results of the preliminary phased array layout gives a quite stable gain ranging from 16.9 dBi to 17.7 dBi over the V-band and offering a ±30° coverage thanks to the expected 3 bits phase shifter for the AP module.

9.3 Backhaul

As mentioned above, high gain antennas are requested for **backhaul**, essentially because distances to cover are high (typically 200m). This high gain can be obtained by using a lens. Two types of lenses were studied: a low-cost plastic lens using 3D printing technology, and a higher end one, based on the transmitarray concept. In this second case, the focal array generates either a fixed beam or a steerable one. A completely different type of antenna is also able to provide high gain and a large bandwidth, at the cost of a higher architecture complexity: the CTS (also considered for Access Point) concept.

- **3D printed dielectric lens** illuminated by a small-size planar patch antenna array (V-band). The performance of several printed arrays have been studied numerically (ST-Fr) and fabricated by Optiprint. These arrays contain 2×2, 4×4, 8×8, 16×16 and 32×32 aperture-coupled patch antennas printed on advanced FR-4 laminates (Panasonic Megtron 6). These arrays have been characterized experimentally using two different set-ups (ST-Fr, Orange). The preliminary results demonstrated that arrays of limited size must be considered to avoid prohibitive insertion losses in the corporate beam forming network. They also show that surface-mounted SMPM connector exhibit high insertion losses. Therefore, the proposed high-gain antenna solution for backhauling at 60 GHz is based on a 2×2 antenna array illuminating a 3D printed dielectric lens. Another possibility is to use the patch antenna developed for the user terminal (Figure 10b).



a) Array antenna at focal point

b) Antenna integrated on interposer with a V-band TRx transceiver

Figure 13 Proposed dielectric lens antenna for backhaul link in V-band

- **Transmitarray** and advanced steerable antennas (V band)
  The discrete lens is composed of seven different phase-shifting unit-cells achieving nearly a 45° phase resolution with a simple dielectric stack-up without any via connection. The seven unit-cells cover the 57-66 GHz with less than 1 dB insertion loss.

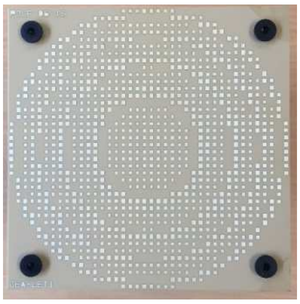
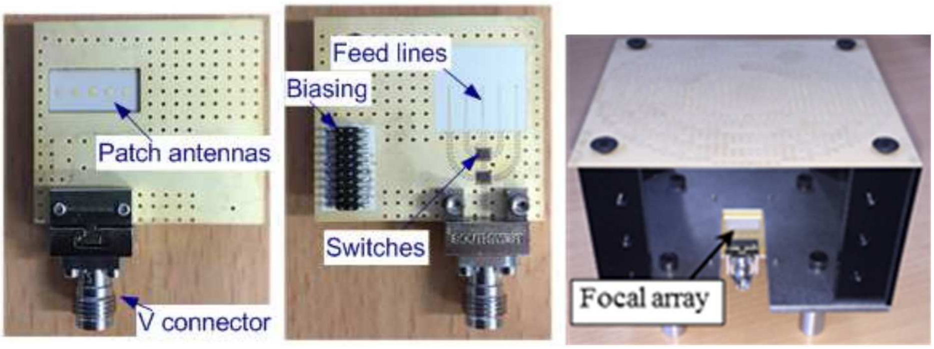


Figure 14 V-Band transmitarray

Two antenna candidates have been selected in which the discrete-lens antenna is combined either with a beam-switching linear focal array or with the phased array developed for the Access Point.

  - **Beam-switching linear focal array**. The focal array has been designed by VTT: it consists of five micro-strip patch antennas combined with two SP3T switches used in a series configuration. The antenna (fabricated by Optiprint) has been characterised experimentally. The entire system provides five beams covering an angular sector of ±6.1° with a gain higher than 26 dBi (not accounting the focal array feeder board loss, estimated to be around 6 dB). The experimental results are presented in Deliverable 4.5.



a) b) c)

Figure 15 switched-beam transmit-array prototype : top view (a) and bottom view (b) of the switched focal array; Photograph of the prototype (c).

  - **Phased-array antenna** developed for Access Point, thus proposing a cost-effective solution using the same or similar integrated transceiver modules developed for the AP). The design of this antenna has been made, but finally not implemented, due to the phase-shifter chip being not functional.

- **Transmitarray** and advanced steerable antennas (E-band)
  - Based on the V-band discrete-lens antenna described above, several designs in E-band were proposed, and several prototypes were fabricated and measured. Using the same multi-layer stack, the unit-cells of the discrete-lens were scaled to the E-band and several lenses were designed to cover either the lower band (71-76 GHz) or the upper band (81-86 GHz) or both (dual-band design). These designs were validated experimentally in fixed-beam configuration (horn antenna used as a focal source) by radiation pattern measurements performed by Telecom Italia. Next, a four-element focal array was designed by UR1 and performances of the lens in switched-beam configuration were simulated. Simulated radiation patterns exhibit four beams covering an angular sector of ±6.6° in the lower band and ±6.9° in the upper band, which is in fairly good agreement with the specifications of backhauling applications. Prototypes have been fabricated and measured.

  - The third antenna system is a E-band **CTS antenna array** fed by a pillbox coupler. The radiating part contains 32 long radiating slots excited by a corporate parallel-plate beam former. The pillbox beam former is designed on a dual-layer organic substrate stack-up. Four electronically switchable beams are radiated in H-plane using a SP4T switch and a pillbox system (Figure 16). A beam intertwining circuit is integrated to improve the beam overlap level. Four different switching networks have been designed by UR1 and VTT. Specific transitions have been also designed and prototyped to further integrate these antennas with Sivers transceivers. Many prototypes were fabricated by Optiprint, assembled by VTT and measured by UR1 and Telecom Italia. The measurement campaigns confirmed the beam switching capability and overall expected antenna performance. Four prototypes have been delivered for the demonstrations.

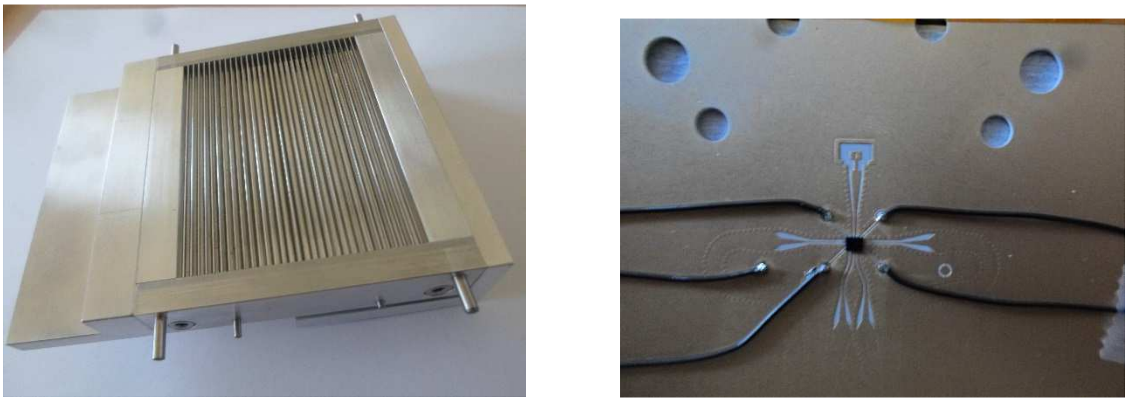


Figure 16 CTS antenna for backhaul link in E-band (left) and zoom on the switch component (right).

9.4 Measurement campaigns

All antenna prototypes have been measured in impedance and radiation, using various facilities available in the consortium.

- The UE antennas were measured at CEA and IMC.
- The AP antennas were characterized as follows:
    - All Rotman lens antennas were measured by VTT.
    - The CTS LTCC antennas were characterized between 50 GHz and 66 GHz. The fixed beam designs were tested both by UR1 and ORA, while the switched beam prototype was measured at UR1. The control boards and firmware for beam-switching were developed by VTT.
- The backhaul antennas were characterized as follows:
    - V-band The fixed beam dielectric lens antennas were measured by ST-FR and ORA.
    - The V-band discrete lens antennas with linear focal array (fixed and switched beams) has been measured by CEA.
    - The CTS fixed beam antennas were measured at ORA and UR1 from 71 to 86 GHz.
    - The CTS steerable antennas were first measured at Telecom Italia from 71 to 75GHz, and then at UR1's premises from 75 to 86GHz.
    - The E-band discrete lens with linear focal array antennas were characterized by Telecom Italia (fixed beam configuration) and at UR1 (steerable beam).

10 Electromagnetic field (EMF) exposure issues

Representative geometries of the antenna module and terminal box have been defined, and relevant use cases have been proposed: phone call position scenario (a mobile terminal is placed against a user's head/ear), and browsing position scenario (investigation of the exposure of the user's hand/finger). For each case, two different possible positions of the antenna module inside the terminal box have been considered: front and edge positions. The numerical model settings, simplifications and simulation constraints have been studied. In particular, it has been shown that the absorption is locally distributed on the user ear's helix and fingertips. Moreover, the presence of the hand in a phone call scenario has been shown to significantly increase the absorption in the head. However, the exposure levels have been demonstrated to not exceed the safety limits recommended by ICNIRP, CENELEC and IEEE. In addition, the user's electromagnetic exposure due to base stations for mmW 5G use cases including backhauling and access has been investigated by Orange. The outcome of this analysis showed that the user’s exposure level is significantly lower than the recommended limitations.

11 Integration and demonstrations

In order to account for delayed radio hardware availability and to manage the associated technical and schedule related risks, it has been decided to split demonstrations into two parallel paths with different time lines and complexities: **Hardware-centric** and **algorithm centric** demonstrationsmainly targeting system tests including real time physical layer processing, MAC protocol processing for closed loop *beam alignment/tracking* .

Hardware-centric demonstrations integrate radio and antenna components developed in MiWaveS with the real-time signal processing capable physical layer of the digital base band system in a unidirectional transmission setup and provide means to adjust radio and antenna related parameters manually. This allowed radio and antenna components developed in MiWaveS to arrive in a very late phase of the project and still measure them with full throughput data rate.

Algorithm-centric demonstrations integrate off-the-shelf V-band phased-array transceiver with the same physical layer as compared to the hardware-centric demonstrations. In addition, algorithm-centric demonstrations comprise integration with real time physical layer control as well as layer 2 MAC functionality, related to beamsteering, in order to implement a closed loop bi-directional mmW link with feedback. The off-the-shelf hardware was available earlier, allowing more time for integration and testing of beam steering algorithms and related protocol functionality.

11.1 integration of analog front-end, implementation of baseband algorithms, and prototyping

11.1.1 Integration of analog RF front-ends

An interfacing module has been defined and manufactured in order to provide a harmonized electrical control interface between National Instruments I/O modules and the different RF components, in particular steerable antennas.

The V band backhaul front-ends utilize the user device node as the focal source for a lens antenna. Two types of V band backhaul nodes have been assembled. One uses a dielectric lens antenna (Figure 13b) while the other uses a planar discrete lens (transmit array) to enhance the antenna gain.

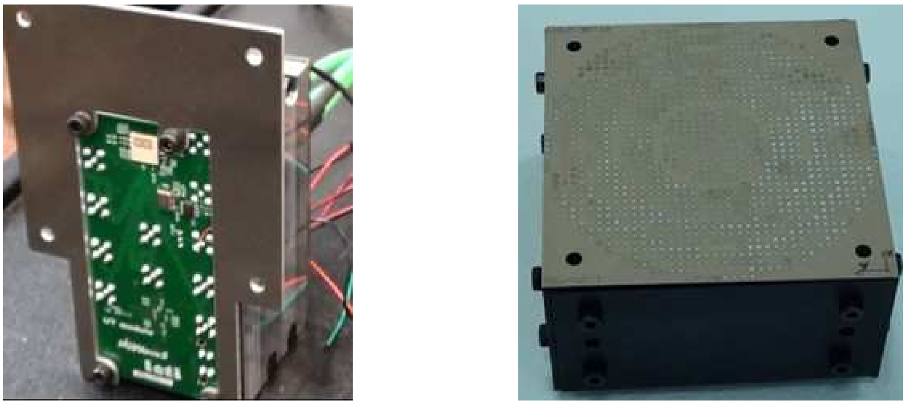


Figure 17: V band backhaul node with the mechanical fixing plate (left) and the discrete lens antenna (right).

In the E band backhaul link experiment a switched beam CTS antenna (Figure 16) with E band frequency converter (Sivers) upgraded to the TDD operation scheme has been used

For the hardware centric access point front-end, a switched beam active Rotman lens Tx and Rx antenna array with a connectorized V band transceiver board has been used.

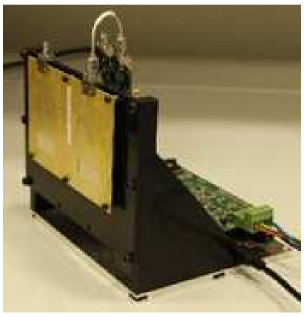


Figure 18 Access Point with Rotman lens and V band transceiver board

In the algorithm centric demonstrations, a commercial V band phased array front-end has been used both as the access point and beam-steered user device.

11.1.2 Digital base band

The digital baseband was developed by National Instruments, and was used in the demonstrations, V-band or E-band, hardware or algoritm centric. Note that it was not used (see Section 11.1.5) for hardware centric demonstrations in CEA premises in Grenoble (France), where a Tektronix signal generator was used instead.

First, the base band hardware and software architecture was developed, based on specifications and requirements defined at the beginning of the project. The baseband was implemented in MiWaveS on a National Instruments PXI platform, which allows modularity and freedom in the choice of the specific hardware parts forming the unit. More in detail, the digital base band consists of a Development / Control Computer for developing PHY and MAC related algorithms and several FPGAs, where real time PHY related functionality such as modulation, demodulation and coding are located. The MAC protocol and PHY control functions are executed on a real-Time Controller. All base band functions are implemented in LabVIEW[3]. ADC, DAC, signal generator and I/O module, which are located in the PXI chassis interface to external devices. The physical layer implements a TDD system with a single carrier (SC) transmission and a Null-CP signal design, which allows low-complexity frequency domain equalization. Modulation and coding as well as the bandwidth and the frame structure of the system were defined. The transmitter and receiver architecture of the proposed SC-scheme and the coding and decoding procedure were implemented in highly parallel fashion on multiple FPGAs, as well as simple synchronization mechanisms. MAC layer components were developed and integrated.

The result of this work is a multi-FPGA based, configurable real time physical layer implementation, capable of supporting 750 MS/s bandwidth and up to 2.3 Gbit/s data rate. This implementation is the interfacing layer between beam steering algorithms and higher layer functionalities on the one hand, and radio and antenna components on the other hand. In particular, this design addresses the following challenges: Real time processing capability, Configurability, Low Complexity, Reliability, Latency, Modularity, Accessibility, Capability of transmitting over realistic mmW hardware.

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[3] LabVIEW is a graphical system design software for test, measurements and software defined radio applications that allows a quick access to hardware prototyping. LabVIEW is a commercial product developed by NI.

11.1.3 Beam forming and multi-user transmission

The implementation and the proof of concept of several beam alignment and beam tracking algorithms for access link and backhaul link were finalized. Based on theoretical considerations and practical constraints, well-suited algorithms for access link and backhaul link have been developed and integrated. This includes the basic exhaustive search and the gradient based alignment algorithm, a low complexity tracking algorithm for the access link and a combined alignment and tracking algorithm for the backhaul link.

Due to the split into algorithmic and hardware centric demonstration paths, the main backhaul outcome is demonstrated in MiWaveS in hardware level only. The exhaustive search, gradient based algorithm and the low complexity tracking algorithm for the mobile access link have been used for algorithmic centric demonstration and have been tested for proper functioning. The protocol and the software infrastructure provide a means to dynamically configure and probe arbitrary beam settings at AP and UD over time. This functionality is essential for the different beam steering algorithms.

11.1.4 Prototyping

Unified radio control software infrastructure was further developed and extended. The control mechanisms allow to control the different backhaul and access radio-antenna combinations through the same base band unit using common IO and FPGA hardware. It abstracts the different properties of different radios away from higher layers. Two modes are supported: real time and non-real time radio and antenna control.. The latter is used for hardware-centric demonstrations where radio and antenna parameters are user-adjustable through a graphical user interface. The former allows algorithms to set radio and antenna parameters synchronously with the slot and radio frame structureby means of the MAC protocol and beam-steering algorithms. This mode is employed by algorithm centric demonstrations.

Secondly, the different integrated radios were connected to and tested with the National Instruments baseband system. The purpose of this activity was to ensure a stable link including base band and radio components.

- The transceiver for V-band from CEA was straightforwardly integrated. However, mechanisms against the influence of the non-ideal effects of transmission (e.g. phase noise and DC offset and I/Q imbalance) had to be developed.
- The E-band transceiver from Sivers: external local oscillator boards as well as IF-to-base band conversion stage from Nokia were added to provide a low phase noise and a high gain range.

In both realtime and non-realtime modes the baseband modem generated the maximum data rate with maximum signal bandwidth.

Significant effort went into testing the over-all system functionality including all sub systems developed. One major aspect was to test the interaction of the beam steering algorithm with the protocol and the radio. Sufficiently low execution time, correct execution order, robustness of operation and error handling within the layered software implementation were key to enable successful demonstrations.

11.1.5 Demonstrations

A total of 8 different demonstrations targeting different objectives have been prepared. Two main experimentation setups were available:

- For the E-band setup, the RF transceiver was provided by Nokia and Sivers and the antenna by UR1.
- For the V-band setup, two versions of the RF transceiver were provided by CEA and ST-Fr, respectively. The CEA version includes integrated antennas while the ST-Fr version provides a generic antenna interface enabling the connection of other partners' antennas.

Both setups use National Instruments's digital baseband hardware including ADC/DAC and the same PHY and MAC software implementation on real-time processing modules. For each of the two setups, a link budget is provided to give more insight about the order of magnitudes of the expected SNR. In contrast, hardware centric demos for access and backhaul in CEA premises in Grenoble use a Tektronix signal generator at the transmitter, and a Tektronix oscilloscope at the receiver instead without error correcting code.

11.1.5.1 Hardware-Centric Backhaul Link Demonstrations

11.1.5.1.1 E Band Backhaul

The MiWaveS E-Band radio and the steerable E-Band CTS antenna (Figure 16) have been demonstrated in outdoor and indoor tests by Nokia and National Instruments at the Nokia campus in Espoo. See Figure 19 for an aerial view of the hop length measurement. These tests focussed mainly on achievable distances under practical propagation conditions (street-level backhaul), as well as the impact of various types of blocking objects and brief outdoor-to-indoor tests and ease of installation. Also indoor corridors and halls as well as windows attenation was tested. For instance, it could be shown that the demonstration system was able to transmit at 1 Gbit/s at 400 m distance and at the maximum supported rate of about 2.3 Gbit/s up to 50 m (750 MHz signal bandwidth).

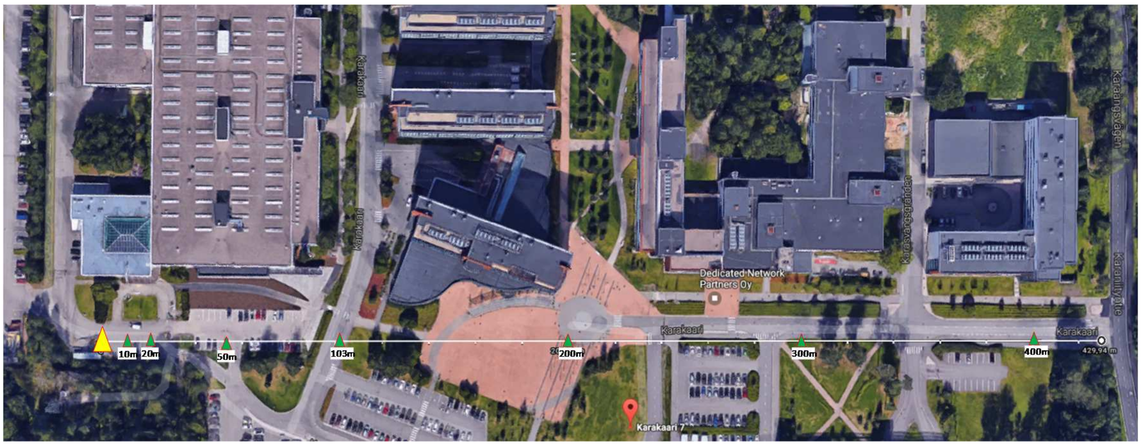

Figure 19. E-Band backhaul hop length measurements at Nokia in Espoo.

11.1.5.1.2 Band V Backhaul

The MiWaveS V-band radio and the dielectric and discrete lens antennas (Figure 13b, Figure 14) have been tested indoors by CEA at CEA in Grenoble. See Figure 20 for the test setup. Tests have been carried out at 25 m link distance by using 16QAM modulation (4.6 Gbps, 15% EVM), and at 70 m link distance by using QPSK modulation (2.3 Gbps, 22% EVM).

Figure 20. V-Band backhaul test at CEA in Grenoble

11.1.5.2 Hardware-Centric Access Link Demonstration

Beam switching and the transmission range of the MiWaveS V-Band access radio including the steerable Rotman lens antenna (Figure 18) at the access point and the user device antenna (Figure 8) at the user device have been carried out indoors by TUD and National Instruments at TU-Dresden. See Figure 21 for an overview of the demonstration setup. During the tests it could be shown that a reliable connection was possible up to about 30 m at a throughput of about 1 GBit/s (QPSK modulation).

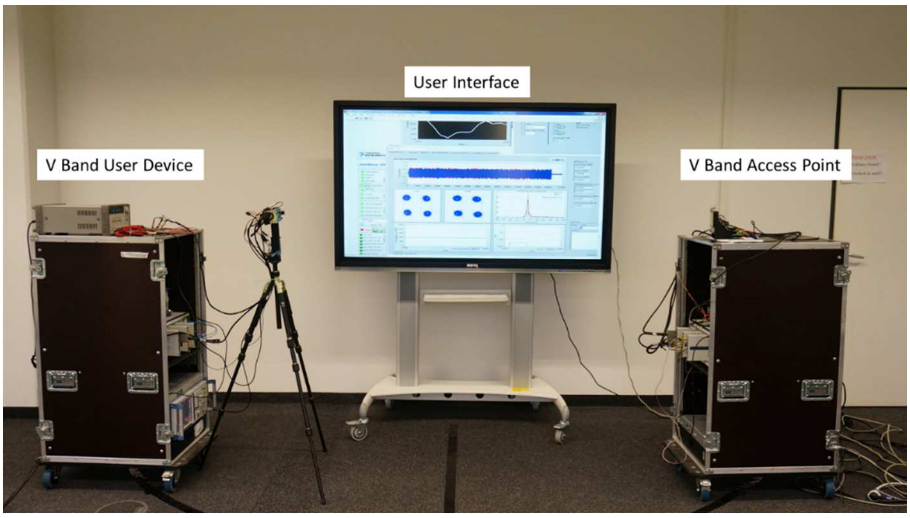

Figure 21. V-Band access link test at TU-Dresden in Dresden.

In addition, another experiment with the same hardware took place in CEA in Grenoble. The difference is that, similar to the Grenoble backhaul experiment, it used an off-the-shelf signal generator with 1,76GHz bandwidth (instead of 750MHz for the NI baseband, used for the Dresden/Espoo experiments). A transmission of 3,5Gbps (QPSK) was observed at 12m. Another test included the TDMA multi-user feature of the Rotman lens antenna. It was observed that the beams formed by the Rotman lens connected to a 4x8 elements antenna array can separate two users at 2m, spaced by 1m.

11.1.5.3 Algorithm-Centric Single and Multi-User Access Link Demonstrations

The properties of the gradient based beam alignment algorithm (Section 7) as well as a beam tracking algorithm have been tested indoors in a single user setup under mobility by TU Dresden at TU Dresden. See Figure 22 for an impression of the test setup. The UD was mounted on a moving robot, automatically following a predefined trajectory, for repetitive tests under mobility. In addition to verifying the overall functionality of the closed loop mmW system, the tests focussed on demonstrating the savings in amount of channel probing as compared to exhaustive search base line beam alignment algorithms.

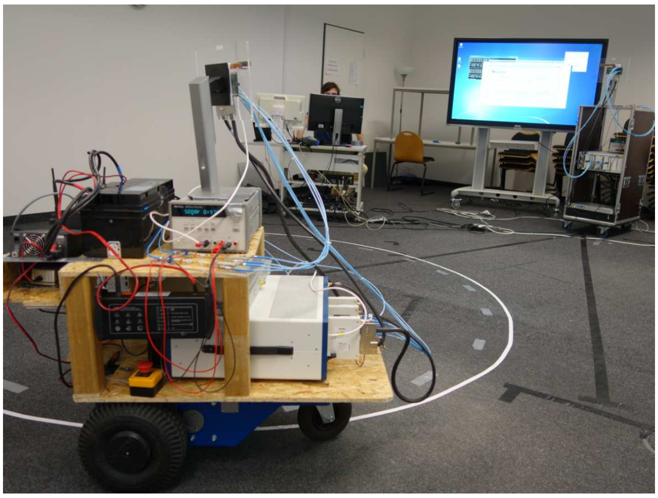

Figure 22. Single User V-Band access link beam steering test including mobility at TU Dresden in Dresden.

In a second step a link of an access point to two users in TDM mode has been demonstrated by TU Dresden and National Instruments at TU Dresden. The tests demonstrated how a mmW link including beam steering could be setup automatically to two user devices positioned at various locations. The link could be maintained under the impact of pedestrian-velocity mobility. In case of a connection loss, the link could be re-established automatically as soon as a beam combination with sufficient receive power was discovered.

11.1.5.4 End-to-End Application Demonstrations

UDP data connectivity has been added to the hardware-centric and algorithm-centric demonstration setups. For the hardware-centric demonstration setup, this data interface allows to connect backhaul and access link and relay a video stream from the base station over the access point to the user device using the E-band and V-band radio and antenna components demonstrated before individually. The demonstration setup, which has been prepared by National Instruments for the final review meeting, is illustrated in Figure 23.

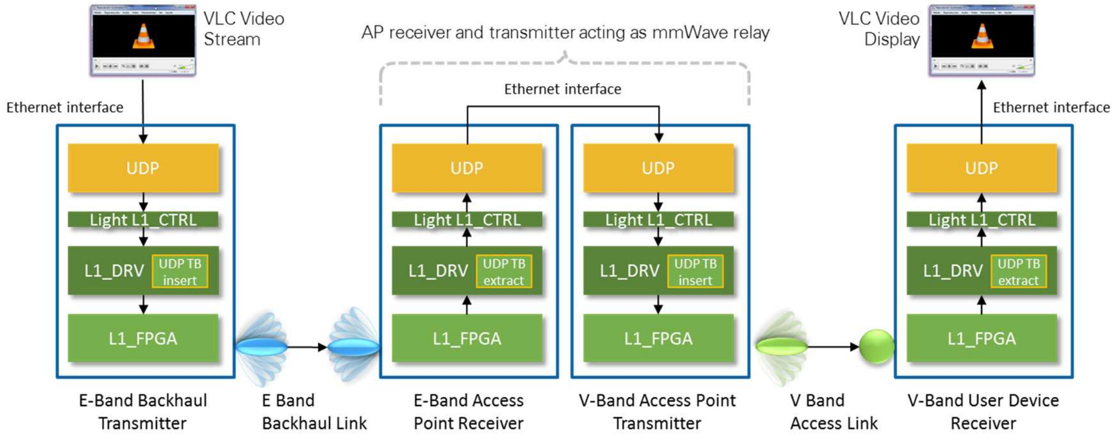

Figure 23. Hardware-centric E-2-E demonstration setup for streaming a video over two mmW hops

The algorithm-centric demonstration setup supports bi-directional UDP data connectivity. UDP tunnelling functionality has been added at the access point and user device side to route IP packets over the V-band mmW link. This functionality allows to access the internet from the user device over the mmW access link, for instance to stream a video. Figure 24 illustrates the respective laboratory setup prepared for demonstration at National Instruments.

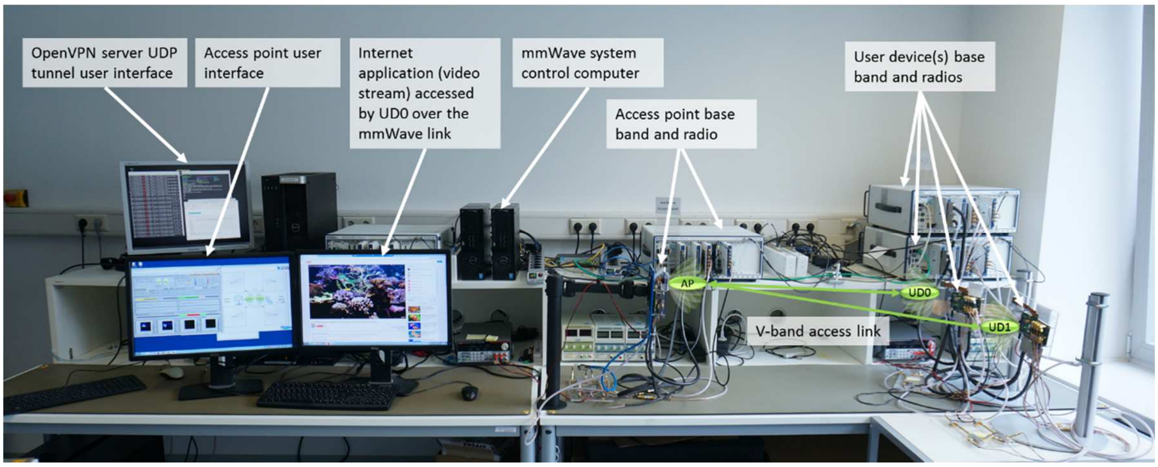

Figure 24. Algorithm-centric V-Band access link end-2-end application setup.

12 Dissemination activities

The dissemination activities have been performed with the objective to ensure that the MiWaveS vision and achievements are widely advertised toward several audiences such as research communities and students (e.g. training schools), industrials, standardisation and regulation bodies, other funded projects and funding agencies**Erreur ! Source du renvoi introuvable.**. The visibility of the project results is a key for a successful impact in the academia and industrial ecosystem, currently defining and pre-developing the future 5G systems. The communication activities target the broadest possible audience and provide information of general interest and about the most recent activities of the project; they involve the maintenance of the MiWaveS web site www.miwaves.eu, the publication of a semestrial newsletter, an annual white paper and press releases for important events. The partners have also dedicated a significant work to the participation of live exhibitions and booths like the Mobile World Conference 2015, NGMN industrial Conference 2016, EuCNC 2016 and EUCNC 2017 conferences, the 5G Summit in order to present the main project results and current demonstration capabilities in direct interaction with the public. An important publication (journals, conferences, workshops, panels, short courses) activity has been conducted as well to disseminate the latest technical results toward the scientific community. More than 100 papers have been published (peer-reviewed journal and conferences, workshops). The consortium was also committed to monitor and impact whenever possible the regulatory and standardization bodies such as ITU-R, 3GPP, ETSI, Ofcom, and ANFR.

13 Conclusion

At the end of the project, it can be said that MiWaveS demonstrated the feasibility of using mmWaves for acces and backhaul, indoors and outdoors, with low cost and low power RF front-ends, compatible with mass market production. Experimental results confirmed that high bit rate transmissions were achievable with the hardware components developed within the prohject, as well in the access link as on the backhaul (Gbits/s).

The main developments in the projects were antennas arrays on organic and LTCC platforms for access and backhaul, that allow beamforming/beamswitching, thus compensating the high path loss at E-band and V-band, while allowing user mobility. Other innovations concerned RF building blocks such as power amplifier, frequency synthetizer and local oscillator. In the two latter cases, the goal was to obtain a very low phase noise. one reason being to enable high modulation orders. The developed RF front-ends have low power consumption, in particular at the mobile side. One key to obtain this result was a very tight integration between RF and antennas. .

On the software side, low-complexity and low latency beam alignment procedures and algorithms were developed. A subset of these was implemented into one of the demonstrators and tested in field trials .

In addition, a new dosimetric methodology was developed to evaluate the electromagnetic exposure due to the terminal at mmWaves. Extensive simulations were performed for various positions of the terminal (near the head, in the hand), and it was found that exposure levels were below safety limits recommended by the standards. The exposure level due to the access points was also evaluated, and it was also found that it was significantly lower compared to the recommended exposure limits.

14 Use and dissemination of foreground

14.1 Section A

A1:* *LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	***Title***	***Main author***	***Title of the periodical or the series***	***Number, date or frequency***	***Publisher***	***Place of publication***	***Year of publication***	***Relevant pages***	***Permanent identifiers[4] (if available)***	***Is/Will open access[5] provided to this publication?***
1.	*Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems?*	*C.Dehos*	*IEEE Communications Magazine*	*vol. 52, no. 9, Sept. 2014,*	*IEEE*		*2014*	*pp.88-95.*	*http://ieeexplore.ieee.org/document/6894457/*	yes
2.	*Active Impedance of Infinite Parallel-Fed Continuous Transverse Stub Arrays*	*F. Foglia Manzillo*	*IEEE Transactions on Antennas and Propagation*	*vol. 63, no. 7, July 2015*	*IEEE*		*2015*	*pp. 3291 - 3297*	*http://ieeexplore.ieee.org/document/7097677/*	yes
3.	*A multilayer LTCC solution for integrating 5G access point antenna modules*	*F. Foglia Manzillo*	*IEEE Microwave. Theory Techn.,*	*vol. 64, no. 7, July 2016.*	*IEEE*		*2016*	*pp. 2272-2283,*	*http://ieeexplore.ieee.org/document/7491239/*	yes
4.	*Massive MIMO Performance with Imperfect Channel Reciprocity and Channel Estimation Error*	*De Mi*	*IEEE Transactions on Communications,*	*Vol 65, n° 9, 2017*	*IEEE*		*2017*	*pp. 3734 - 3749*	*http://ieeexplore.ieee.or*	yes

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[4] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[5] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

									g/document /7867037/	
5.	*Hybrid Beamforming for Large Antenna Arrays With Phase Shifter Selection*	*S.Payami*	*IEEE Transactions on Wireless Communications,*	*vol. 15, no. 11, Nov. 2016.*	*IEEE*		*2016*	*pp. 7258 - 7271*	*http://ieeexplore.ieee.org/document/7542170/*	yes
6.	*A Low-Profile Broadband 32-Slot Continuous Transverse Stub Array for Backhaul Applications in E-Band*	*T.Potelon*	*IEEE Trans. Antennas and Propagation*		*IEEE*		*2017*		*http://ieeexplore.ieee.org/document/7942043/*	yes
7.	*Mode matching analysis of an E-plane 90° bend with a square step in parallel plate waveguide*	*F. Foglia Manzillo*	*IEEE Antennas and Wireless Propagation Letters,*	*Vol 16, 2017*	*IEEE*		*2017*	*pp. 2187 - 2190*	*http://ieeexplore.ieee.org/document/7929349/*	yes
8.	*Insights Into Phase-Noise Scaling in Switch-Coupled Multi-Core LC VCOs for E-Band Adaptive Modulation Links*	*L. Iotti*	*IEEE Journal of Solid-State Circuits*	*Issue 7 - July 2017*	*IEEE*		*2017*	pp:1703 - 1718	*http://ieeexplore.ieee.org/document/7948734/*	yes
9.	*1.29 W/mm2 23 dBm 66 GHz Power Amplifier in 55nm SiGe BiCMOS with In-Line Coplanar Transformer Power Splitters and Combiner*	*D. Pepe*	*IEEE Microwave and Wireless Components Letters*	*The article has been accepted for inclusion in a future issue of this journal*	*IEEE*		*2017*			
10.	*Advanced radio technology to support mobile traffic growth*	*L.Dussopt*	*EU Research,*	*vol. 2015, Issue 1,*	*Blazon Publishing and Media Ltd*		*2015*	*pp. 66-67.*		yes
11.	*PCB Technology Requirements for Millimeter-Wave Interconnect and Antenna*	*J.Francey*	*The PCB Magazine*	*April 2017,*	*I-Connect007*		*2017*	*pp 47 – 52 China pp 36-43 ROW*	*http://iconnect007.uberflip.com/i/808383-pcb-apr2017/36*	*Yes*
12.	*PCB Technology Requirements for Millimeter-Wave Interconnect and Antenna*	*J.Francey*	*Journal of the Institute of Circuit Technology*	*volume 10 no. 2*	*Institute of Circuit Technology*		*2017*	*pp 7-12*		*No*

13.	*Antenna/ human body interactions in the 60 GHz band: state of knowledge and recent advances*	*M.Zhadobov*	*Book Chapter in “State-of-the-art in Body-Centric Wireless Communications and Associated Applications”*		*IET*	*pp.97-142*	*2016*			yes
14.	*Millimeter-Wave Antennas for Radio Access and Backhaul in 5G Heterogeneous Mobile Networks*	*L.Dussopt*	*9th European Conference on Antennas and Propagation (EuCAP)*	*12-17 April 2015*	*IEEE*	*Lisbon, Portugal*	*2015*		*http://ieeexplore.ieee.org/document/7228822/*	yes
15.	*Modeling and Design of Parallel-Fed Continuous Transverse Stub (CTS) Arrays*	*F. Foglia Manzillo*	*9th European Conference on Antennas and Propagation (EuCAP)*	*12-17 April 2015*	*IEEE*	*Lisbon, Portugal*	*2015*		*http://ieeexplore.ieee.org/document/7228411/*	yes
16.	*A long slot array fed by a multilayer true-time delay network in LTCC for 60 GHz communications*	*F. Foglia Manzillo*	*10th European Conference on Antennas and Propagation (EuCAP)*	*11-15 April 2016.*	*IEEE*	*Davos, Switzerland*	*2016*		*http://ieeexplore.ieee.org/document/7481701/*	yes
17.	*Millimetre-wave beam-switching Rotman lens antenna designs on multi-layered LCP substrates*	*J.Säily*	*10th European Conference on Antennas and Propagation (EuCAP)*	*11-15 April 2016.*	*IEEE*	*Davos, Switzerland*	*2016*		*http://ieeexplore.ieee.org/document/7481212/*	yes
18.	*A switched-beam linearly-polarized transmitarray antenna for V-band backhaul applications*	*A.Moknache*	*10th European Conference on Antennas and Propagation (EuCAP)*	*11-15 April 2016.*	*IEEE*	*Davos, Switzerland*	*2016*		*http://ieeexplore.ieee.org/document/7481257/*	yes
19.	*Gain enhanced millimetre-wave beam-switching Rotman lens antenna designs on LCP*	*A.Lamminen*	*11th European Conference on Antennas and Propagation (EuCAP)*	*19-24 March 2017*	*IEEE*	*Paris, France*	*2017*		*http://ieeexplore.ieee.org/document/7928483/*	yes
20.	*Switched-Beam E-Band Transmitarray Antenna for Point-to-Point Communications*	*L.Dussopt*	*11th European Conference on Antennas and Propagation (EuCAP)*	*19-24 March 2017*	*IEEE*	*Paris, France*	*2017*		*http://ieeexplore.ieee.org/document/7928369/*	yes
21.	*V-band transceiver modules with integrated antennas and phased*	*L.Marnat*	*11th European Conference on*	*19-24 March 2017*	*IEEE*	*Paris, France*	*2017*		*http://ieeexplore.ieee.or*	yes

	arrays for mmWave access in 5G mobile networks		*Antennas and Propagation (EuCAP)*						*g/document /7928489/*	
22.	*Broadband CTS Antenna Array at E-band*	*T.Potelon*	*11th European Conference on Antennas and Propagation (EuCAP)*	*19-24 March 2017*	*IEEE*	*Paris, France*	*2017*		*http://ieeexplore.ieee.org/document /7928290/*	yes
23.	*Wideband multibeam arrays of long slots fed by quasi-optical systems*	*F. Foglia Manzillo*	*11th European Conference on Antennas and Propagation (EuCAP)*	*19-24 March 2017*	*IEEE*	*Paris, France*	*2017*		*http://ieeexplore.ieee.org/document /7928424/*	yes
24.	*Parallel fed 2*1 antenna array utilizing surface wave cancellation on LTCC substrate*	*J.Hagn*	*11th European Conference on Antennas and Propagation (EuCAP)*	*19-24 March 2017*	*IEEE*	*Paris, France*	*2017*		*http://ieeexplore.ieee.org/document /7928258/*	yes
25.	*A Broad-Band 55-nm BiCMOS T/R Switch for mmW 5G Small Cell Access Point*	*V.Puyal*	*14th IEEE Int. New Circuits and Systems Conf. (NEWCAS)*	*26-29 June 2016*	*IEEE*	*Vancouver, Canada.*	*2016*		*http://ieeexplore.ieee.org/document /7604750/*	yes
26.	*A multi-core VCO and a frequency quadrupler for E-Band adaptive-modulation links in 55nm BiCMOS*	*L.Lotti*	*ESSCIRC 2016 42nd European Solid-State Circuits Conference*	*Sept. 12-15, 2016*	*IEEE*	*Lausanne, Switzerland.*	*2016*		*http://ieeexplore.ieee.org/document /7598319/*	yes
27.	*A highly linear bidirectional phase shifter based on vector modulator for 60GHz application*	*F.Hameau*	*International Microwave Symposium IMS 2017,*	*4-9-th June 2017,*	*IEEE*	*Honolulu, Hawaï*	*2017*		*http://ieeexplore.ieee.org/document /8058971/*	yes
28.	*Effective Beam Alignment Algorithm for Low Cost Millimeter Wave Communication*	*T.Kadur*	*IEEE VTC Fall 2016*	*18–21 September 2016*	*IEEE*	*Montréal, Canada*	*2016*		*http://ieeexplore.ieee.org/document /7880977/*	yes
29.	*Joint Beam and Frequency Scheduling for Millimeter-wave Downlink Multiplexing*	*H.Miao*	*IEEE VTC Spring 2017*	*4-7 June 2017*	*IEEE*	*Sidney, Australia*	*2017*		*http://ieeexplore.ieee.org/document/7504304/*	yes

30.	*A Low-Complexity Beamforming Method by Orthogonal Codebooks for Millimeterwave Links*	*H.L.Chiang*	*IEEE ICASSP 2017*	*5-9 March 2017*	*IEEE*	*New Orleans, USA*	*2017*		*http://ieeexplore.ieee.org/document/7952782/*	yes
31.	*A compact and high-gain Ka-band multibeam continuous transverse stub antenna*	*M.Ettore*	*IEEE AP-S Symp. on Antennas and Propagation,.*	*19-25 July 2015,*	*IEEE*	*Vancouver, B.C., Canada*	*2015*		*http://ieeexplore.ieee.org/document/7304722/*	yes
32.	*mmWave Use cases and Prototyping: a way towards 5G Standardization*	*V.Frascolla*	*European Conference on Networks and Communications (EuCNC 2015),*	*June 29-July 2, 2015.*	*IEEE*	*Paris, France*	*2015*		*http://ieeexplore.ieee.org/document/7194054/*	yes
33.	*Enabling Wireless Backhauling for Next Generation mmWave Networks*	*M.Shariat*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*IEEE*	*Paris, France*	*2015*		*http://ieeexplore.ieee.org/document/7194061/*	yes
34.	*From Use Cases to Prototyping Multi-Gbit/s mmWave Links in MiWaveS*	*E.Ohlmer*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*IEEE*	*Paris, France*	*2015*			no
35.	*Millimeter-Wave Electromagnetic Field Exposure from Mobile Terminals*	*A.R. Guraliuc*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*IEEE*	*Paris, France*	*2015*		*http://ieeexplore.ieee.org/document/7194045/*	yes
36.	*Self-organized Multi-hop Millimeter-wave Backhaul Network: Beam Alignment and Dynamic Routing*	*H.Miao*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*IEEE*	*Paris, France*	*2015*		*http://ieeexplore.ieee.org/document/7194083/*	yes
37.	*Millimeter-Wave Technologies for 5G: Opportunities, Challenges and path toward Standards (invited paper)*	*L.Dussopt*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*IEEE*	*Paris, France*	*2015*			no
38.	*mmWave Small Cell Networks: First E Band Backhaul Prototyping Results in MiWaveS*	*E.Ohlmer*	*European Conference on Networks and Communications (EuCNC 2016)*	*June 27-July 30, 2016.*	*IEEE*	*Athens, Greece*	*2016*			no

39.	Recent Progress on Millimeter-Wave Radios and Antennas for Wireless Access and Backhaul in 5G Mobile Networks	L.Dussopt	European Conference on Networks and Communications (EuCNC 2016), Special Session	June 27-July 30, 2016.	IEEE	Athens, Greece	2016			no
40.	Next-Generation Millimetre-Wave for 5G and Beyond	E.Calvanese Strinati	European Conference on Networks and Communications (EuCNC 2016), Special Session	June 27-July 30, 2016.	IEEE	Athens, Greece	2016			no
41.	5G E-band Backhaul System Evaluations - Focus on Moving Objects and Outdoor to Indoor Transmission	Z.Du	European Conference on Networks and Communications (EuCNC 2017)	12-15 June 2017	IEEE	Oulu, Finland	2017		http://ieeexplore.ieee.org/document/7980764/	yes
42.	Low-Complexity Spatial Channel Estimation and Hybrid Beamforming for Millimeter Wave Links	H.L.Chiang	IEEE International Symposium On Personal, Indoor And Mobile Radio Communications (PIMRC'16),	4-7 September 2016	IEEE	Valencia, Spain	2016		http://ieeexplore.ieee.org/document/7794710/	yes
43.	User exposure at millimeter waves: electromagnetic and thermal dosimetry in V-band	A.R.Guraliuc	European Microwave Week	2-7 Oct. 2016		London, UK,	2016			no
44.	5G E-band Backhaul System Measurements in Urban Street-Level Scenarios	Z.Du	European Microwave Week EUMC 2017	9-12 October 2017		Nürnberg, Germany	2017			no
45.	A strategy for research projects to impact standards and regulatory bodies - The approach of the EU-funded project MiWaveS	V.Frascolla	IEEE Conf. on Standards for Communications and Networking (CSCN 2015),.	28-30 Oct. 2015	IEEE	Tokyo, Japan,	2015		http://ieeexplore.ieee.org/document/7390415/	yes
46.	Improved Uplink I/Q-Signal Forwarding for Cloud-Based Radio Access Networks with Millimeter Wave Fronthaul	J.Bartelt	12th Int. Symp. on Wireless Communication Systems (ISWCS 2015),	25–28 August 2015	IEEE	Brussels, Belgium.	2015		http://ieeexplore.ieee.org/document/7454359/	yes

47.	*Full rank spatial channel estimation at millimeter wave systems*	*H.L.Chiang*	*International Symposium on Wireless Communication Systems (ISWCS'16),*	*20-23 Sept. 2016*	*IEEE*	*Poznan, Poland*	*2016*		*http://ieeexplore.ieee.org/document/7600852/*	yes
48.	*Effective RF Codebook Design and Channel Estimation for Millimeter Wave Communication Systems*	*S.Payami*	*2015 IEEE Int. Communication Workshop (ICC 2015)*	*8-12 June 2015*	*IEEE*	*London, UK.*	*2015*		*http://ieeexplore.ieee.org/document/7247345/*	yes
49.	*Millimeter-Wave Communications in 5G Mobile Networks for Wireless Access and Backhaul*	*L.Dussopt*	*1st Int. Forum on Research and Technologies for Society and Industry (RTSI),.*	*16-18 Sept. 2015*		*Torino, Italy*	*2015*			no
50.	*A low-profile and high-gain continuous transverse stub antenna using PCB-air hybrid technology*	*T.Potelon*	*IEEE AP-S Symp. On Antennas and Propagation*	*26 June-1 July 2016*	*IEEE*	*Puerto-Rico.*	*2016*		*http://ieeexplore.ieee.org/document/7696560/*	yes
51.	*A V-band antenna module based on vertical TEM waveguides fully integrated in LTCC*	*F. Foglia Manzillo*	*IEEE AP-S Symp. On Antennas and Propagation*	*26 June-1 July 2016*	*IEEE*	*Puerto-Rico.*	*2016*		*http://ieeexplore.ieee.org/document/7695902/*	*yes*
52.	*Hybrid Beamforming Strategy for Wideband Millimeter Wave Channel Models*	*H.L.Chiang*	*The 21st International ITG Workshop on Smart Antennas (WSA'17),*	*15-17 March 2017*	*IEEE*	*Berlin, Germany*	*2017*		*http://ieeexplore.ieee.org/document/7955952/*	*yes*
53.	*PCB Technology Requirements for Millimeter-Wave Interconnect and Antenna*	*J.Francey*	*EIPC Winter Conference, Salzburg,*	*2 & 3 February 2017*		*Salzburg, Austria*	*2017*			*no*
54.	*MM-Wave Radio and Antenna Technologies for Wireless Access and Backhaul*	*L.Dussopt*	*European Conference on Networks and Communications (EuCNC 2014), “Enablers on the road to 5G” workshop,*	*June 23-26, 2014.*		*Bologna, Italy*	*2014*			*no*

55.	*Challenges and opportunities for millimeter-wave mobile access standardisation*	*V.Frascolla*	*IEEE GLOBECOM 2014, Workshop on Telecommunications Standards - From Research to Standards*	*8-12 Dec. 2014*	*IEEE*	*Austin, Tx., USA*	*2014*		*http://ieeexplore.ieee.org/document/7063490/*	*Yes*
56.	*5G Cellular Wireless: Challenges, Solutions and Early Prototyping*	*V. Kotzsch*	*International ITG Workshop on Smart Antennas*	*12 March 2014.*		*Nuremberg, Germany*	*2014*			*no*
57.	*Radio Resource Management for Heterogeneous Millimeter-wave Backhaul and Access Network*	*M.Shariat*	*IEEE Int. Conf. on Communications (ICC), Workshop on 5G RAN Design*	*23-27 May 2016*	*IEEE*	*Kuala Lumpur, Malaysia.*	*2016*		*http://ieeexplore.ieee.org/document/7503856/*	*Yes*
58.	*Analyses of Orthogonal and Non-Orthogonal Steering Vectors at Millimeter Wave Systems*	*H.L.Chiang*	*5GB2P IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM'16)*	*21 - 21. June..2016*	*IEEE*	*Coimbra, Portugal,*	*2016*	*/*	*http://ieeexplore.ieee.org/document/7523581*	*no*
59.	*Communications en bande millimétrique pour les futurs réseaux mobiles (5G) (invited presentation)*	*L.Dussopt*	*19èmes Journées Nationales Microondes (JNM 2015)*	*2-5 June2015*		*Bordeaux, France.*	*2015*			*no*
60.	*Conception d'un commutateur SPDT TX/RX en technologie BiCMOS 55 nm en bande V pour la 5G*	*V.Puyal*	*19èmes Journées Nationales Microondes (JNM 2015)*	*2-5 June 2015*		*Bordeaux, France.*	*2015*			*no*

A2: LIST OF DISSEMINATION ACTIVITIES

N°	Type of activities[6]	Main leader	Title	Date/Period	Place	Type of audience[7]	Size of audience	Countries addressed
1.	*Publication*	*CEA*	*IEEE Communications Magazine*	*vol. 52, no. 9, Sept. 2014,*				
2.	*Publication*	*Université de Rennes 1*	*IEEE Transactions on Antennas and Propagation*	*vol. 63, no. 7, July 2015*				
3.	*Publication*	*Université de Rennes 1*	*IEEE Microwave. Theory Techn.,*	*vol. 64, no. 7, July 2016.*				
4.	*Publication*	*University of Surrey*	*IEEE Transactions on Communications,*	*Vol 65, n° 9, 2017*				
5.	*Publication*	*University of Surrey*	*IEEE Transactions on Wireless Communications,*	*vol. 15, no. 11, Nov. 2016.*				
6.	*Publication*	*Université de Rennes 1*	*IEEE Trans. Antennas and Propagation*	*Accepted 2017*				

7.	Publication	Université de Rennes 1	IEEE Antennas and Wireless Propagation Letters,	Vol 16, 2017				
8.	Publication	CEA	EU Research,	vol. 2015, Issue 1,				
9.	Publication	Optiprint	The PCB Magazine	April 2017,				
10.	Publication	Optiprint	Journal of the Institute of Circuit Technology	volume 10 no. 2				
11.	Conference	CEA, Université de Rennes 1	9th European Conference on Antennas and Propagation (EuCAP)	12-17 April 2015	Lisbon, Portgal	Scientific	1000	All
12.	Conference	Université de Rennes 1, VTT, CEA, Optiprint	10th European Conference on Antennas and Propagation (EuCAP)	11-15 April 2016.	Davos, Switzerland	Scientific	1000	
13.	Workshop	Intel	10th European Conference on Antennas and Propagation (EuCAP)	11-15 April 2016.	Davos, Switzerland	Scientific	50	
14.	Conference	VTT, Université de Rennes1, CEA, Orange, Optiprint, Intel	11th European Conference on Antennas and Propagation (EuCAP)	19-24 March 2017	Paris, France	Scientific	1300	
15.	Special Session	Université de Rennes 1, CEA	11th European Conference on Antennas and Propagation (EuCAP)	19-24 March 2017	Paris, France	Scientific	100	
16.	Conference	ST-I	PRIME 2016	27 – 30 June 2016	Lisbon, Portugal	Scientific		
17.	Conference	CEA	14th IEEE Int. New Circuits and Systems Conf. (NEWCAS)	26-29 June 2016	Vancouver, Canada	Scientific		
18.	Conference	ST-I	ESSCIRC 2016	Sept. 12-15, 2016,.	Lausanne, Switzerland	Scientific		

19.	*Conference*	*Technical University of Dresden*	*IEEE VTC Fall 2016*	*18–21 September 2016*	*Montréal-Canada*	*Scientific*		
20.	*Conference*	*Intel*	*IEEE VTC Spring 2017*	*4-7 June 2017*	*Sidney, Australia*	*Scientific*		
21.	*Conference*	*Technical University of Dresden*	*IEEE ICASSP 2017*	*5-9 March 2017*	*New Orleans, USA*	*Scientific*		
22.	*Conference*	*Université de Rennes 1*	*IEEE AP-S Symp. on Antennas and Propagation*	*19-25 July 2015*	*Vancouver, B.C., Canada*	*Scientific*	*2000*	
23.	*Conference*	*Intel, National Instruments, Nokia, CEA, University of Surrey, Telecom Italia, Université de Rennes 1*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*Paris, France*	*Scientific*	*500*	
24.	*Panel*	*CEA*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*Paris, France*	*Scientific*		
25.	*Special Session*	*Intel*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*Paris, France*	*Scientific*		
26.	*Booth*	*National Instruments*	*European Conference on Networks and Communications (EuCNC 2015)*	*June 29-July 2, 2015.*	*Paris, France*	*Scientific*		
27.	*Conference*	*CEA, National Instruments,*	*European Conference on*	*June 27-July 30, 2016.*	*Athens, Greece*	*Scientific*	*500*	

		Nokia, VTT, Telecom Italia, Sivers IMA, Université de Rennes 1	Networks and Communications (EuCNC 2016)					
28.	Booth	CEA, National Instruments, Intel, Nokia	European Conference on Networks and Communications (EuCNC 2016)	June 27-July 30, 2016.	Athens, Greece	Scientific		
29.	Special Session	Intel	European Conference on Networks and Communications (EuCNC 2016)	June 27-July 30, 2016.	Athens, Greece	Scientific		
30.	Conference	Nokia, National Instruments	European Conference on Networks and Communications (EuCNC 2017)	12-15 June 2017	Oulu, Finland	Scientific	600	
31.	Workshop	Université de Rennes 1, VTT, CEA,	EuCNC '17	12-15 June 2017,	Oulu, Finland	Scientific	50	
32.	Workshop	Technical University of Dresden, Nokia	EuCNC '17,	12-15 June 2017,	Oulu, Finland	Scientific		
33.	Booth, demos, videos	Technical University of Dresden, Nokia, National Instruments, CEA	EuCNC '17,	12-15 June 2017,	Oulu, Finland	Scientific		
34.	Conference	Technical University of Dresden	IEEE International Symposium On Personal, Indoor And Mobile Radio	4-7 September 2016	Valencia, Spain	Scientific		

			Communications (PIMRC'16),					
35.	Workshop	CEA, ST-Fr	European Microwave Week 2015, workshop on Millimeter-Wave Technologies for 5G Mobile Networks	Sept. 6-11, 2015,	Paris, France.	Scientific	60	
36.	Conference	Université de Rennes 1, CEA	European Microwave Week	2-7 Oct. 2016	London, UK	Scientific	1500	
37.	Conference	Nokia, National Instruments	European Microwave Week	9-12 October 2017	Nürnberg, Germany	Scientific	1500	
38.	Conference	Intel, University of Surrey, National Instruments, CEA, Université de Rennes 1, Nokia	IEEE Conf. on Standards for Communications and Networking (CSCN 2015)	28-30 Oct. 2015	Tokyo, Japan,	Scientific		
39.	Conference	CEA	19èmes Journées Nationales Microondes (JNM 2015),	2-5 Juin 2015	Bordeaux, France.	Scientific	500	
40.	Conference	Technical University of Dresden	12th Int. Symp. on Wireless Communication Systems (ISWCS 2015),	25–28 August 2015	Brussels, Belgium.	Scientific		
41.	Conference	Technical University of Dresden	International Symposium on Wireless Communication Systems (ISWCS'16),	20-23 Sept. 2016	Poznan, Poland	Scientific		
42.	Conference	University of Surrey	2015 IEEE Int. Communication Workshop (ICC 2015)	8-12 June 2015	London, UK.	Scientific		

43.	Conference	CEA, Telecom Italia	1st Int. Forum on Research and Technologies for Society and Industry (RTSI),.	16-18 Sept. 2015	Torino, Italy	Scientific		
44.	Conference	Université de Rennes 1, Optiprint, Orange, VTT	IEEE AP-S Symp. On Antennas and Propagation	26 June-1 July 2016,	Puerto-Rico.	Scientific		
45.	Conference	Technical University of Dresden	The 21st International ITG Workshop on Smart Antennas (WSA'17),	15-17 March 2017	Berlin, Germany	Scientific		
46.	Conference	CEA	International Microwave Symposium IMS 2017,	4-9-th June 2017,	Honolulu, Hawaï	Scientific		
47.	Conference	Optiprint	EIPC Winter Conference, Salzburg,	2 & 3 February 2017	Salzburg,Austria	Industry		
48.	Conference	Nokia	Brooklyn 5G Summit	23-25 April 2014.	Brooklyn, New York, USA	Scientific		
49.	Conference	CEA, Nokia	Brooklyn 5G Summit	8-10 April 2015.	Brooklyn, NY, USA	Scientific		
50.	Book Chapter	Université de Rennes 1	Antenna / human body interactions in the 60 GHz band: state of knowledge and recent advances	IET Digital Library, 2016	Chapter 5 in “State-of-the-art in Body-Centric Wireless Communications and Associated Applications”	Scientific		
51.	Workshop	CEA	European Conference on Networks and Communications (EuCNC), “Enablers	June 23-26, 2014.	Bologna, Italy,	Scientific		

			on the road to 5G” workshop,					
52.	Workshop	CEA	Future Networks 12th FP7 Concertation, Radio Access and Spectrum (RAS) Cluster Meeting,	22 Oct. 2013.	Brussels, Belgium	Scientific		
53.	Conference	CEA	INTEL European Research & Innovation Conference (ERIC 2013)	22-23 Oct. 2013	Nice, France	Scientific & Industry		
54.	Workshop	CEA	International Workshop on Cloud Cooperated Heterogeneous Networks (project MIWEBA),	23 Oct. 2013.	Osaka, Japan	Scientific		
55.	Workshop	CEA	Korea-EU Workshop: Exploring common research interests in the Future Internet,	Sept. 30 - Oct. 1, 2013	Seoul,, Korea	Scientific		
56.	Workshop	CEA	Future Internet Assembly, " Radio Access and Spectrum Innovations for 5G"	18-20 March 2014	Athens, Greece	Scientific		
57.	Workshop	Intel, CEA, Université de Rennes 1, Telecom Italia, Nokia, TST	IEEE Globecom 2014, Workshop on Telecommunications Standards - From Research to Standards	8-12 Dec. 2014	Austin, Tx., USA	Scientific		
58.	Workshop	National Instruments	IEEE GLOBECOM 2014, Industry Forum	8-12 Dec. 2014	Austin, Tx., USA	Industry		

59.	Workshop	CEA	IEEE GLOBECOM 2014, Industry Forum	8-12 Dec. 2014	Austin, Tx., USA	Industry		
60.	Workshop	CEA	Scientific Days of the URSI French Chapter	25-26 May 2014.	Paris, France	Scientific		
61.	Workshop	National Instruments	International ITG Workshop on Smart Antennas,	12 March 2014.	Nuremberg, Germany	Scientific		
62.	Publication	CEA	RAN WORLD 2015	Jan. 20-21, 2015.	Dusseldorf, Germany,	Industry		
63.	Booth	Nokia, National Instruments	Mobile World Congress 2015	2-5 march 2015	Barcelona, Spain	Industry		
64.	Press Release	CEA	Announcing MiWaveS at the Mobile World Congress	3 March 2015		Industry	Sent to 250 media	
65.	Workshop	CEA	2015 IEEE Radio Frequency Integrated Circuits Symposium (RFIC 2015), workshop "mmW to THz, which applications with which technology",	17-19 May 2015.	Phoenix, AZ, USA	Scientific		
66.	Workshop	ST-Fr	"Antenna and Packaging Technologies for mmWave Front-End Integration" workshop, IEEE Microwave Week	17-22 May 2015.	Phoenix, AZ, USA	Scientific		
67.	Workshop	ST-Fr	“MmW to THz, which Applications with which Technology” workshop, IEEE Microwave Week	17-22 May 2015.	Phoenix, AZ, USA	Scientific		

68.	Workshop	CEA	Radio Access and Spectrum (RAS) Cluster Workshop, 2015 European Conference on Networks and Communications (EuCNC 2015),	June 29-July 2, 2015.	Paris, France,	Scientific		
69.	Workshop	National Instruments	GLOBECOM 2015, Industry Forum	6-10 Dec 2015	San Diego, CA, USA	Industry		
70.	Posters	Intel, Nokia, National Instruments	GLOBECOM 2015, Industry Forum	6-10 Dec 2015	San Diego, CA, USA	Industry		
71.	Video	Nokia, National Instruments	GLOBECOM 2015, Industry Forum	6-10 Dec 2015	San Diego, CA, USA	Industry		
72.	Roundtable	National Instruments	RF Roundtable, TU Vienna	11.-12. Nov 2015	Vienna, Austria	Industry		
73.	Workshop	CEA	Workshop on millimetre-wave technology for high-speed broadband wireless networks,	20 Nov. 2015	Valencia, Spain,.	Scientific	50	
74.	Workshop	CEA	Int. Microwave Symp. (IMS) workshop How mm-wave systems reshape the future of telecom and sensing applications" workshop, Int.	22-27 May 2016.	San Francisco, CA, USA	Scientific	200	
75.	Workshop	CEA	Int. Microwave Symp. (IMS) workshop "Millimeter-wave R&D for 5G: Systems, phased arrays, and handset transceivers"	22-27 May 2016.	San Francisco, CA, USA	Scientific	200	

76.	Workshop	ST-FR	Int. Microwave Symp. (IMS) workshop, “Millimeter-wave R&D for 5G: Systems, phased arrays, and handset transceivers”	22-27 May 2016	San Francisco, CA, USA	Scientific	200	
77.	Workshop	Intel	Workshop at the 10th European Conf. on Antennas and Propagation (EuCAP),	10-15.April 2016	Davos, Switzerland	Scientific	50	
78.	Workshop	Nokia	IEEE WCNC'2016 Workshop on Millimeter Wave-Based Integrated Mobile Communications for 5G Networks	3 April 016	Doha, Qatar,	Scientific		
79.	Panel + Session chair	CEA	IEEE WCNC'2016 Workshop on Millimeter Wave-Based Integrated Mobile Communications for 5G Networks	April 3rd 2016	Doha, Qatar,	Scientific		
80.	Panel	CEA	10th International Conference on Cognitive Radio Oriented Wireless Networks,	April 2nd 2015	Doha, Qatar	Scientific		
81.	Workshop	University of Surrey, Nokia	IEEE Int. Conf. on Communications (ICC), Workshop on 5G RAN Design	23-27 May 2016,	Kuala Lumpur, Malaysia.	Scientific		

82.	Workshop	CEA	EU-Taiwan Workshop on 5G Research,	24 Oct. 2014.	Brussels, Belgium,	Scientific	100	
83.	Panel	CEA	2014 IEEE International Conference on Ultra-Wideband (ICUWB 2014), ,	1-3 Sept. 2014.	Paris, France	Scientific	200	
84.	Booth	National Instruments	5G Revolution Dinner (co-located with 3GPPP RAN meeting in Dresden)	20 Aug. 2014	Dresden, Germany	Industry		
85.	Panel	CEA	IEEE Vehicular Technology Conf. VTC-Spring) 2015,	11-14 May 2015.	Glasgow, Scotland,	Scientific		
86.	Workshop	CEA	European Microwave Week workshop, “Millimetre-Wave Technologies for 5G Mobile Networks and Short-Range Communications"	3-7 Oct. 2016.	London, UK,	Scientific	60	
87.	Workshop	Technical University of Dresden	5GB2P IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM'16),	21 - 21. June..2016	Coimbra, Portugal,	Scientific		
88.	Workshop	CEA	ADTC	8-10 May 2017	Dresden, Germany,	Scientific	100	
89.	Workshop	Optiprint	“Institute of Circuit Technology Spring Seminar”	14 March 2017	Meriden, UK	Industry		

90.	Booth	Technical University of Dresden, National Instruments	NGMN industrial Conference	12-13 October 2016,	Frankfurt Germany	Scientific		
91.	Booth, Workshop	Technical University of Dresden	5G Summit	19 September 2016	Dresden, Germany	Scientific		
92.	Summer School	Université de Rennes 1, CEA	European School on Antennas	4-8 July 2016	Rennes, France	Scientific	30	
93.	Short course	Technical University of Dresden	Course at TUD	During winter semester Oct. 2015- Feb. 2016.				
94.	Short course	University of Surrey	Course at University of Surrey	March 2015, and every month of march in the further years				
95.	PhD. Thesis	University of Surrey	"Massive MIMO with imperfect channel state information and practical limitations" D. Mi	2017	Guildford, UK			
96.	PhD. Thesis	University of Surrey	"Hybrid beamforming for massive MIMO systems" S. Payami	2017	Guildford, UK			
97.	PhD. Thesis	Université de Rennes 1	"Compact and wideband antenna solutions for next generation wireless networks in MM-Band" F. Foglia Manzillo	March 2017	Rennes, France			
98.	PhD. Thesis	Université de Rennes 1	"Etude et conception d'antennes multi	To be defended in 2017				

			faisceaux en bandes V et E pour les futures réseaux cellulaires hétérogènes 5G » T. Potelon					
99.	*PhD. Thesis*	*Technical University of Dresden*	*2 thesis ongoing*					
100.	*Website*	*CEA*	*www.miwaves.eu*	*Since May 2014*				
101.	*Twitter*	*CEA*	*@FP7_MiWaveS*	*Since April 2014*				
102.	*Newsletters*	*CEA*	*5 Newsletters available on the website, sent to industrial and academic contacts, including other funded project coordinators, EC members, and Industrial Advisory Board members*	*July 2014, April 2015, December 2015, July 2016, January 2017*				
103.	*White Paper*	*CEA*	*White paper*	*Jan 2015*				
104.	*White Paper*	*Telecom Italia, National Instruments*	*White Paper*	*June 2016*				
105.	*Flyer*	*CEA*	*Available on the web site*	*Since the beginning of the project*				
106.	*Press release*	*CEA*	*"Leading European communications companies and research organisations have launched*	*28 Aug. 2014*				

			an EU project developing the future 5th Generation cellular mobile networks”					

14.2 Section B (Public)

14.2.1 Part B1

TABLE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[8]:	**Confidential Click on YES/NO**	**Foreseen embargo date dd/mm/yyyy**	**Application reference(s)**	**Subject or title of application**	**Applicant (s) (as on the application)**
Patent	YES	21/10/2016	US 62/066787	Self-organized multi-hop millimeter wave backhaul to support dynamic routing and cooperative transmission	Honglei Miao, Michael Farber
Patent	NO		FI20165803	Wideband aperture coupled elliptical dipole antenna	Antti Lamminen
Patent	Yes	21/05/2018	FR 1654845 US 15358350	Array of synchronous coupled oscillators	Emmanuel Chataigner

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Patent	NO		US201615146977	An oscillator circuit, corresponding apparatus and method	L. Iotti. A. Mazzanti. A. Pallotta. F. Svelto
Patent	NO		UA2016A003549	An active transformer, corresponding apparatus and method	L. Larcher, A. Pallotta
Patent	NO		UB2015A005245	Amplificatore push-pull, apparecchiatura e procedimento corrispondenti	A. Pallotta

14.2.2 Part B2

Type of Exploitable Foreground[9]	**Description of exploitable foreground**	**Confidential Click on YES/NO**	**Foreseen embargo date dd/mm/yyyy**	**Exploitable product(s) or measure(s)**	**Sector(s) of application**[10]	**Timetable, commercial or any other use**	**Patents or other IPR exploitation (licences)**	**Owner & Other Beneficiary(s) involved**
1- Commercial exploitation of R&D results	*VCO circuit architecture for high spectral efficiency wireless link applications*	*YES*	*31/12/2017*	*mmw VCO IPR*	*Wireless Telecommunications*	*2019*	*see table B1*	*ST*
2-Commercial exploitation of R&D results	*Very compact Power Amplifier and driver for mmw link applications*	*YES*	*31/12/2017*	*mmw PA and PPA IPR*	*Wireless Telecommunications*	*2019*	*see table B1*	*ST*
3- Commercial exploitation of R&D results	*Antenna flat lens using organic dielectric substrate and photolithography technology- Transmit array technology at millimeter waves (fixed beam)*	*No*		*38 dBi V band antenna* *43 dBi E band antenna*	*Wireless Telecommunications*	*2017*	*NA*	*CEA*

1&2

- *Its purpose*
  Analysing the wireless network technology evolution, ST, in order to increase his market share in RF products, is adding the E-band transceiver related ICs to his portfolio, promoting at the same time, a BiCMOS based low cost and low power technology well working within the mmWave frequency range. The above mentioned circuit functional IP, developed during the project timeframe and related to the E-band transceiver analogue front end enrich the ST standard IP cell portfolio in order to allow the customers who prefer to approach the ASIC business model, to concentrate their efforts mainly towards the application specific system aspects, where their know-how give the strongest added value.
- *How the foreground might be exploited, when and by whom*
  By the activities done in MiWaveS, ST offers to customers involved in the mmWave back and front hauling market both an advanced BiCMOS-based technology allowing to develop their own E-band transceiver analog front end solution or the critical IPs to design an E-band transceiver analog front end chip set, enabling the development of their E-band RRH equipment at lower costs respect to apparatus solutions based on more expensive III-V technology chip set.
- *IPR exploitable measures taken or intended*
  ST could also expand its available market by including solutions, both in term of customer-on-technology (COT) and critical IPs as well, for mmWave-based small cell backhaul in its portfolio – a market area that is likely to scale up with the increasing demand for data capacity. The exploitation plan followed by ST, to exploit the RF IC designed IP, consists of three different kinds of business models starting as the pure “Wafer foundry” service through the ASIC approach and finally leading to the valuable ASSP chip set solution provider.
- *Further research necessary, if any*
  The results obtained in the project foster ST to pursue further in the research activities related to developing a full silicon based E-band chip set in order to tackle the ASSP market business model, where the profit margin per product unit are maximized.
- *Potential/expected impact (quantify where possible)*
  Conservatively, a range of 10-15% of the near future Mobile Backhaul Market can be addressed with an E-Band equipment. Under this assumption, the forecast for E-Band market in 2017 can be estimated close to 700M€. Conservatively, in 2017, an estimated market for the E-band equipment related to the small cell backhauling of about 60% of the total backhauling market results in a forecast for E-Band small cell backhaul market of about 415M€.

3

- *Its purpose*
  Exploitation of a discrete lens antenna concept at millimeter waves for industrial application by designing antenna products dedicated to backhauling. Compact antenna dimensions and low cost are key industrial criteria for large production

- *How the foreground might be exploited, when and by whom*
  The antenna concept demonstrated in the project has been developed for industrial manufacturing. First products are available in E band in the Radiall company (a CEA-LETI customer) catalog

- *IPR exploitable measures taken or intended*
- *Further research necessary, if any*
- *Potential/expected impact (quantify where possible)*
  Alternative antenna products for backhauling in E and V band can contribute to extend the offer with a new antenna form factor. It allows Radiall to penetrate a new telecom market for 5G antenna infrastructure. 20% of the potential market is expected by Radiall.

15 Report on societal implications

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	619563
Title of Project:	MiWaveS
Name and Title of Coordinator:	Sylvie MAYRARGUE, Project Manager at CEA-LETI

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***No***
2. Please indicate whether your project involved any of the following issues (tick box) :	***YES***
RESEARCH ON HUMANS	
• Did the project involve children?	NO
• Did the project involve patients?	NO
• Did the project involve persons not able to give consent?	NO
• Did the project involve adult healthy volunteers?	NO
• Did the project involve Human genetic material?	NO
• Did the project involve Human biological samples?	NO
• Did the project involve Human data collection?	NO
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	NO
• Did the project involve Human Foetal Tissue / Cells?	NO
• Did the project involve Human Embryonic Stem Cells (hESCs)?	NO
• Did the project on human Embryonic Stem Cells involve cells in culture?	NO
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	NO
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	NO
• Did the project involve tracking the location or observation of people?	NO
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	NO
• Were those animals transgenic small laboratory animals?	NO
• Were those animals transgenic farm animals?	NO
• Were those animals cloned farm animals?	NO
• Were those animals non-human primates?	NO
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	NO

- Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	NO
DUAL USE	
- Research having direct military use	No
- Research having the potential for terrorist abuse	NO

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	**Number of Women**	**Number of Men**
Scientific Coordinator	1	1
Work package leaders	1	7
Experienced researchers (i.e. PhD holders)	2	31
PhD Students	1	7
Other	2	19

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	**3**
Of which, indicate the number of men:	3

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	○ ■	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
☐	Design and implement an equal opportunity policy	○	○	○	○	○
☐	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
☐	Organise conferences and workshops on gender	○	○	○	○	○
☐	Actions to improve work-life balance	○	○	○	○	○
○	Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

■ No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

■ Yes- please specify: Summer schools, short courses, at the University

○ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

■ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

○ Main discipline[11]: 2.2

○	Associated discipline[11]:	○	Associated discipline[11]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ ●	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

● No

○ Yes- in determining what research should be performed

○ Yes - in implementing the research

○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

○ No
○ Yes- in framing the research agenda
○ Yes - in implementing the research agenda
● Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

● Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
○ No

13b If Yes, in which fields?

Agriculture
Audiovisual and Media
Budget
Competition
Consumers
Culture
Customs
Development Economic and Monetary Affairs
Education, Training, Youth
Employment and Social Affairs

Energy
Enlargement
Enterprise
Environment
External Relations
External Trade
Fisheries and Maritime Affairs
Food Safety
Foreign and Security Policy
Fraud
Humanitarian aid

Human rights
Information Society
Institutional affairs
Internal Market
Justice, freedom and security
Public Health
Regional Policy
Research and Innovation
Space
Taxation
Transport

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[11] Insert number from list below (Frascati Manual).

13c If Yes, at which level?

○ Local / regional levels
○ National level
● European level
● International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**13**
To how many of these is open access[12] provided?	**On going**
How many of these are published in open access journals?	**0**
How many of these are published in open repositories?	**On going**
To how many of these is open access not provided?	
Please check all applicable reasons for not providing open access:	
☐ publisher's licensing agreement would not permit publishing in a repository ☐ no suitable repository available ☐ no suitable open access journal available ☐ no funds available to publish in an open access journal ☐ lack of time and resources ☐ lack of information on open access ☐ other[13]: ……………	
15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**5**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	
	Registered design	
	Other	**1 License**

17. How many spin-off companies were created / are planned as a direct result of the project?	**None**
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

☐ Increase in employment, or
☐ Safeguard employment, or
☐ Decrease in employment,
☒ Difficult to estimate / not possible to quantify

☐ In small & medium-sized enterprises
☐ In large companies
☐ None of the above / not relevant to the project

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[12] Open Access is defined as free of charge access for anyone via Internet.

[13] For instance: classification for security project.

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	☒

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes ● No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ● No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

- ☒ Press Release
- ☐ Media briefing
- ☐ TV coverage / report
- ☐ Radio coverage / report
- ☐ Brochures /posters / flyers
- ☐ DVD /Film /Multimedia
- ☐ Coverage in specialist press
- ☐ Coverage in general (non-specialist) press
- ☐ Coverage in national press
- ☐ Coverage in international press
- ☒ Website for the general public / internet
- ☐ Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

- ☐ Language of the coordinator
- ☐ Other language(s)
- ☒ English