1 MiWaveS – towards millimetre wave small cell networks

This White Paper follows the overview over the project structure and goals provided in [1] and has the goal of introducing the main results obtained throughout the second year of the project.

The MiWaveS (Beyond 2020 heterogeneous wireless network with Millimetre Wave Small cell access and backhauling) project aims to contribute some key aspects to the ongoing definition of 5G, i.e. the next generation of wireless telecommunications [2]. Specifically, it will show how high-throughput and low-latency heterogeneous mobile networks, based on flexible spectrum usage of the millimetre wave (mmW) frequency bands at 57–86 GHz, should work. The project’s objectives are to define and demonstrate solutions to:

- Provide mobile access to content-rich data using a fast and broadband link,
- Reduce the overall network EMF density (blue radio),
- Reduce the power consumption of the small cell access and backhaul links (green radio),
- Increase the flexibility and the Quality of Service (QoS) and decrease operating expenses of operators’ networks.

The second year of the project provides some key milestones in transitioning from the system concepts developed in the first year to arrive at the proof-of-concept planned at the end of the project. In particular, the following Sections provide an overview of the main technical activities (mmW system design, mmW radio transceiver and antenna design, prototyping and demonstration), by highlighting not only the key results obtained, but also the lessons learnt and areas of improvement. Reference to public deliverables and detailed results are also provided.

2 Millimetre wave system design

The work on system design has focused on improving the global power efficiency of the network infrastructure, and enhancing data routing and smart beam steering at backhaul and access point in order to provide a network that is reliable, easy and efficient to deploy and operate for operators and provides quality-controlled mobile access. The following sections provide a highlight of solutions investigated in the Project. Please refer to [3] for a detailed presentation of results.

2.1 Beam steering

Our work addresses three main topics: Beamforming algorithms for access links, effective RF codebook design and channel estimation for mmW (backhaul) communication systems, and assessment of beamswitching and beamsteering capabilities of antennas including implementation impairments.

The proposed beam alignment algorithm for access links targets implementation in a system with realistic hardware constraints. Simulations show that this algorithm reduces computation complexity significantly from 256 evaluations in exhaustive antenna beam search to 40 evaluations and 4 feedback iterations, where the initiator and responder each have a uniform linear antenna array of 8 antennas and 16 beams. Simulations show that the number of scatterers in the channel has no notable influence on the performance of the system. In particular the proposed optimization algorithm is robust in a sense that it is able to step from local minima to the global minimum (see Figure 2-1).

In addition, the work resulted in a practical RF codebook, based on a genetic algorithm, for analogue and hybrid beamforming schemes where the antenna array is equipped with low-resolution phase shifters. It is shown that a low-complexity 2-bit phase shifter can provide acceptable performance in terms of the array gain towards different spatial directions, compared with the phase shifters with infinite resolution. This significantly reduces the hardware complexity.

Furthermore, we proposed a low-complexity channel estimation algorithm based on an enhanced one-sided search [4]. For a backhaul channel, characterized by a low number of multi-path components, analogue beam-switching with...
limited steering range is a promising approach. It has also been shown that analogue beam-switching can achieve a significant fraction of the performance of singular value decomposition-based beamsteering.

The impact of four major types of impairments - phase noise, carrier frequency offset, IQ imbalance and mast vibration [5] - were assessed with a link level simulator. For each of these real-life imperfections, compensation algorithms were proposed which illustrate how to cope with these impairments in a practical transmission system.

Figure 2-1. Contour plot of example beam forming cost function with four iterations and final result (red). The algorithm is able to step from a non-optimal minimum to the best minimum.

2.2 Routing and radio resource management (RRM)
The proposed generic HetNet structure (Figure 2-2) [6] can support all MiWaves use cases. In particular, several deployment examples are provided to demonstrate the network dimensioning. Multi-connectivity with control and data plane split is presented to address the roles of macro cells and mmW small cells. The following sub-sections provide some examples of the results obtained.

Figure 2-2. HetNet architecture with mmW Small Cell layer.

2.2.1 RRM in mmW networks
Theoretical work derived two decomposition alternatives, i.e. node-centric and path-centric, that decouple radio resource management optimization into two sub-problems. A joint beam-frequency multiuser rate scheduling algorithm for mmW downlink system has been developed.
2.2.2 Functions and algorithms for the backhaul
A self-organized link establishment procedure for a multi-hop in-band mmW access point relay backhaul is introduced. 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 backhaul link as a secondary link.

For a dedicated standalone mmW backhaul, we have described a system which builds up autonomously without assuming wireless wide-area signalling on the control plane. It is a transparent sub-network that offers first-mile connectivity between small-cell access points and the macro base station. The proposed 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.

2.2.3 System functions for the access link
Based on the existing 3GPP LTE RACH (random access channel) procedure, a macro-cell assisted mmW user equipment random access method has been introduced. The proposed random access method employs a new RACH channel consisting of multiple preamble sequences. As a result, the uplink beam alignment is achieved as the complement to downlink beam alignment setup.

It is also proposed a two stage cell detection and measurement method that reduces the initial cell search burden and feedback overhead significantly.

2.2.4 Energy efficient operation
By deploying IP-based middleware and interchanging information between users and the network at control plane, it is possible to trigger network-centralized decisions so as to balance the traffic and allocate users at the best base station at each moment. We simulated a system where a 24-hour load period is generated and tested over several possible scenarios and it is possible to see high potential gains in terms of overall QoS of the network.

We also show with an example how an ultra-high speed mmW network layer in heterogeneous networks can contribute to energy savings. A large number of network elements can spend most of the time in low-power sleep mode without deteriorating network service. Some potential topologies and network layouts are described modelling the network organization, traffic load and cell layouts. A study evaluating the potential and theoretical energy savings is carried out to provide advice on the best way to deploy and manage mmW small cells.

3 Millimetre wave radio transceivers
In the MiWaveS project, 5G small cell access points with interconnecting backhaul links are demonstrated at millimetre-wave frequencies. The access with user terminals occurs in the V-band, whereas backhaul links are demonstrated both at V- and E-band. Several transceivers are needed in the demonstrations: transceivers for V and E-band backhauling, transceivers for V-band access point and user terminal. This section describes concisely the transceivers and building blocks under development in the project. The transceiver integration with antennas has been one key design driver in the development.

3.1 V-band 65nm CMOS transceiver chip
STMicroelectronics and CEA provide V-band 65 nm CMOS transceiver chips to the MiWaveS project (Figure 3-1) [7]. The circuit is applicable both to WiGiG/802.11ad and backhaul applications. It is a fully integrated MMIC circuit including a transmitter, receiver and VCO&PLL circuitry to cover the 4 IEEE channels defined between 57 and 66 GHz. The frequency generation of the local oscillator signals is common both to the transmitter and receiver, which use a double-stage frequency conversion scheme with an IF frequency of 20 GHz. The transceiver chip has baseband I&Q Tx inputs/Rx outputs for the direct connection with the digital baseband sub-system. The chip size is 2.8*3.3 mm². Furthermore, a cost-effective BGA (Ball Grid Array) flip-chip module has been fabricated to ease the assembly of the transceiver on a standard application printed circuit board (PCB). In the MiWaveS project, this transceiver chip is utilized in the 60 GHz backhaul radio, user terminal radio but also as a building block in the V-band phased array access point front-end module.

![Figure 3-1. 60 GHz transceiver chip realized in 65 nm CMOS technology](image-url)
3.2 V-band user terminal transceiver
The 65nm CMOS transceiver chip is used in the 60 GHz user terminal module (Figure 3-2). The module is built on a multi-layer liquid crystal polymer (LCP) substrate having a size of 10*10 mm². The transceiver chip is flip-chipped on the bottom side of the module. On the top side, two separate linearly-polarized fixed-beam aperture-coupled patch antennas are used one for reception and another for transmission. The module is further soldered (BGA) on a larger PCB for test and demonstration purposes. The interface between the module and PCB includes differential 50 ohms Rx and Tx baseband I/Q signals, digital control signals and transceiver supply voltage lines. A low power consumption has been one important design driver.

3.3 V-band access point transceiver
The phased-array access point front-end includes the 60 GHz CMOS transceiver presented above, a Tx/Rx duplex switch, a power splitter, four bidirectional phase shifter/amplifier chips and 2x4 patch antenna elements. The transceiver and SPDT (Single Pole Double Throw) duplex switch are common to all antenna array elements, while separate low noise amplifier, power amplifier, switch and phase shifter circuits feed each antenna. The Tx/Rx duplex SPDT switch in 55 nm BiCMOS technology has been designed, fabricated and measured [8]. Its size is 0.9x0.9 mm². The phase-shifter/amplifier chip was designed in 55nm BiCMOS technology as well and its size is 2.0x3.4 mm². It includes two- and one-bit switched passive phase shifters in a series configuration to obtain a 3-bit phase shifter with a 45 degrees phase resolution. The low noise amplifier consists of three stages. The first stage uses a common source FET transistor while the second and third stages use a common emitter BJT transistor. Currently, the active phase shifter chip is in characterization. The LCP interposer board, which will integrate the antenna array with the active chips and transceiver, is under design; its size will be 19x19 mm² for a 2x4 elements antenna array. This compact phased-array transceiver module will be the first demonstration of a scalable multi-chip architecture for 60-GHz phased arrays and will meet various system level requirements for mmW access.

3.4 E-band backhaul transceiver
Siemens provides the 71-76 GHz transceiver modules to the MiWaveS E-band backhaul demonstration. The existing transceiver has been augmented by external LO (Local Oscillator) and AFE (Analog Front-End) boards. The external Rx/Tx local oscillators with on/off switching allow the transceiver use in TDD (Time Division Duplex) operation scheme. The AFE board provides the IF to baseband frequency conversion required for interfacing with the baseband platform. In order to avoid the leakage of the power amplifier broadband noise to the receiver input, a commercial SPDT duplex waveguide switch has been added to the transceiver waveguide Rx input/Tx output ports. In addition to the TDD operation mode, low phase noise has been a key design driver.

3.5 Millimetre-wave building block development
In the course of the transceiver development, two performance parameters have been identified to be of key importance. In backhaul links, the transmitter shall provide a high output power with a good linearity. The trend in millimetre-wave backhaul radios is towards multi-level modulation schemes such as 16, 32, 64, 128 and 256 QAM in order to increase the data rate. This sets a strict constraint 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 high efficiency.

3.5.1 60 GHz power amplifier
The performance of 28 nm CMOS FD-SOI (Fully Depleted Silicon on Insulator) technology has been illustrated by designing, fabricating and testing a 60 GHz reconfigurable power amplifier [9]. The realized amplifier achieves an outstanding performance in terms of a Power Added Efficiency of 21% at saturated output power, a 1 dB output compression point of 18.2 dBm and 74 mW power consumption.
3.5.2 V- and E-band frequency synthesizer
STMicroelectronics has developed a frequency synthesizer in 55 nm BiCMOS technology operating both at V- and E-band. The frequency synthesizer includes a unique fractional PLL and DCXO (Digitally Controlled Crystal Oscillator) to comply with all V- and E-band radio channel allocations. The 40-GHz VCO is followed by a frequency doubler in order to achieve the V- or E-band LO frequency. Emphasis in the design has been on flexibility and high integration level. The measured phase noise at 75.6 GHz at 1 MHz carrier offset is –97.7 dBc/Hz.

3.5.3 E-band local oscillator chain
The local oscillator chain consists of a 20-GHz multi-core VCO followed by two frequency doublers in a series configuration (Figure 3-3). The re-configurability of the multi-core VCO has been successfully proved by switching on and off the VCO cores. The VCO can be configured to operate with one, two or four tank circuits. By doubling the number of active tank circuits, the phase noise reduces by 3 dB. The VCO and frequency doublers have been realized using a 55 nm BiCMOS technology. The purpose is to switch on more VCO cores as the number of modulation levels goes up.

3.5.4 E-band power amplifier
An E-band DDAT (Double Distributed Active Transformer) power amplifier in 55 nm BiCMOS technology has been designed and fabricated. The final stage of the amplifier is based on a power combining technique. The distributed output transformer combines the power from four power cells. Similarly, a distributed transformer is used at the input of the power cells. An output power over 20 dBm is targeted.

3.5.5 Investigation on efficient power amplifiers
Various modulation and coding schemes are applied in mmW high data rate backhaul and access links. These signals can be expected to have large PAPRs (peak-to-average power ratios). The highest efficiency point of a power amplifier typically locates close to the saturated power region but the linearity constraints require the amplifier to operate at an average output power several dBs below the saturated output power and this back-off degrades considerably the amplifier efficiency. In order to circumvent the linearity-efficiency trade-off, it is necessary to control dynamically the load resistance or DC bias voltage of the power amplifier. While such dynamic linearization techniques have been widely investigated in literature at low GHz wireless frequencies, the MiWaveS project has investigated their feasibility 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, which show a high efficiency (PAE) at lower microwave frequencies, have been selected in this investigation and the performed simulations indicate that a Doherty amplifier gives a clear performance advantage compared to a balanced power amplifier configuration also at mmW frequencies.

4 Millimetre wave antenna design
MiWaveS develops the new antenna technologies involved in its vision of future mobile networks with mmW access and backhaul. These antenna systems target three different types of devices, namely mobile user terminals, access points and backhaul radios. They have been selected from system-level specifications, detailed state-of-the-art, and demonstration objectives set in the project. These design activities rely on an intensive use of electromagnetic solvers and are supported, when needed and/or possible, by intermediate prototyping and experimental characterisations (S-parameters and radiation performance). They 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. Examples of antenna prototypes are provided in Figure 4-1.
In the first case (f band), various antennas with fixed or steerable beams have been studied. The first one is a flat antenna array combined with a Rotman lens (RL) beam-forming network (BFN), Figure 4-1 (left). The Rotman lens beam-former is broad-band and, in spite of the passive structure, it provides equal phase states as a 3-bit phase shifter. Two RL with 5 beam ports or 9 beam ports have been designed on multi-layered LCP substrates. The RL with 5 beam ports has been combined to 1×8, 2×8, and 4×8 aperture-coupled patch antenna arrays. The five beam-port branches of the RL have been combined with two TGS4305-FC SP3T switches from TriQuint [10].

The second antenna under consideration is based on CTS (Continuous Transverse Stub) concepts; this approach allows reaching a very broad bandwidth, at the expense of a complex antenna architecture. Several fixed beam CTS arrays were designed, manufactured, and tested. Very good experimental results (26% impedance bandwidth, 15 dBi peak gain at 60 GHz, stable radiation properties) were obtained [11],[12].

Finally, the third antenna system under study is a highly-flexible phased array antenna. The module contains an RF transceiver IC, power splitters & combiners, T/R switches as well as phase-shifting and amplifying RFICs for beam-steering. This concept is modular and allows a flexible selection of the number of array elements; it provides also an optimal placement of amplification stages close to each antenna element in order to minimize interconnection losses and maximize power efficiency. An antenna array containing eight elements (four in azimuth and two in elevation) has been designed.

4.3 Directive antennas for backhauling in V- and E-bands
Various antennas with fixed or steerable beams have been studied. In the first case (fixed beams in V-band), the performance of several printed arrays has been studied in V-band. These arrays contain 2×2, 4×4, 8×8, 16×16 and 32×32 aperture-coupled patch antennas printed on advanced FR-4 laminates. To maximize the antenna efficiency, the selected high-gain antenna architecture is based on a 2×2 antenna array illuminating a 3D-printed dielectric lens (Figure 4-1 (middle)).
In the second case (steerable beams), three antenna candidates have been selected. The first two antenna candidates operate in the V-band and consist of a discrete-lens antenna (Figure 4-1 (right)) combined either with a beam-switching linear focal array or with a phased array. The discrete lens is composed of seven different phase-shifting unit-cells achieving nearly a 45° phase resolution with a simple stack without any via connection. The seven unit-cells cover the 57-66 GHz with less than 1 dB of insertion loss. The beam-switching focal array consists of five patch antennas combined with two single-pole triple-throw (SP3T) switches used in a series configuration. 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) [13]. The current work targets the use of a 2x4 elements phased-array as a focal source in order to extend the beam-steering coverage to 6°×13° and minimize the gain variation within this sector to less than 3 dB.

The third antenna system is an E-band wide bandwidth CTS antenna array fed by a pillbox coupler. The radiating part contains 32 long radiating slots excited by corporate parallel plate beam formers. The pillbox beam former is designed on a dual-layer organic substrate stack-up. The preliminary experimental results demonstrate broadband performances covering the entire E-band [14].

4.4 Exposure assessment and evaluation of antenna/human body interaction

The objective is to assess electromagnetic field exposure and evaluate the antenna/human body interactions in the 60-GHz band. Representative geometries of the antenna module and terminal box have been defined, and relevant use cases have been proposed and simulated [15][16]: 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). In each case, the numerical model settings, simplifications and simulation constraints have been studied. In each case, two different possible positions of the antenna module inside the terminal box have been considered: front and edge positions [15]. The numerical analysis generally demonstrated that the obtained equivalent incident power density is lower than the recommended ICNIRP (International Commission on Non-Ionizing Radiation Protection) safety limits.

5 Millimetre wave prototyping and demonstration

The primary goals of this activity are to integrate and demonstrate the feasibility of key technology components developed within the project, such as mmW steerable antennas, in access and backhaul link settings but also to test important aspects of system concepts developed by project partners. These goals are achieved in several steps:

- Firstly, (steerable) antennas and RF transceiver components in V-band and E-band are integrated into several RF transceiver nodes with appropriate signal and control interfaces.
- Secondly, a common real time mmW physical layer, following the proposal [17], is implemented into an FPGA-based digital base band hardware system.
- Thirdly, portions of higher layers, focussing primarily on beam steering algorithms and protocols are implemented.
- Finally, three above mentioned subsystems are integrated into base station, access point and user device mmW prototypes.

The resulting prototypes are then demonstrated in propagation scenarios typical of mmW access and backhaul link settings.

5.1 Selected challenges and how they are addressed:

MiWaveS is unique in that each of the 15 project partners contributes components, software or know-how to the prototyping and demonstration activities. On the one hand, tremendous expertise in all relevant fields, ranging from algorithm and protocol research down to semiconductor processes can be leveraged. On the other hand, a significant logistical effort has to be managed in terms of time lines, team distribution all over Europe, use of common tools and alignment on common interfaces. It is fair to say that integration of the different subsystems into a working prototype can be considered to be one of the largest challenges but also achievements.

Integration of Diverse RF Subsystems: These subsystems range from integrated RF and antennas to systems built out of discrete components. Each subsystem has its very own RF performance characteristics and RF parameter control methodology. The challenge is to integrate these different systems with a common real time digital base band implementation. This challenge is approached by introducing an intermediate integration step – a physical layer.
simulation system equipped with hardware-in-the-loop capabilities. This tool allows to easily access all parts of the physical layer in simulation, while replacing the simulated mmW channel with a transmission over the same base band and mmW RF hardware components that are being used in the real time mmW prototypes. This allows, for instance to study, design and test impairment compensation methods.

**Interfaces:** The challenge is to control the characteristics of a multitude of RF and antenna components, for instance gain settings or beam characteristics, through a common control source which is part of the digital base band. This challenge is approached by designing dedicated interfacing hardware modules which condition control signals, originating from the digital base band, to properly drive the individual control functionalities of the different RF and antenna modules.

**Beam Steering Protocol Development:** The challenge is to develop and test beam-steering algorithms by a multitude of teams in parallel to the actual real time base band and RF component research and development, i.e., without full availability of hardware and software stack. This challenge is addressed by developing a beam-steering integration software environment which comprises in part the same higher-layer software components and interfaces used in the real time implementation but abstracts physical layer and hardware. This environment allows to integrate different beamsteering methods in absence of prototyping hardware and test their correct functionality but also their real time execution characteristics. After successful test and integration, these algorithms will be transferred into the actual real time prototyping system.

### 5.2 First results

A first milestone comprises the backhaul transmission in E-band using directive antennas. The software user interface and a complete mmW node are shown in Figure 5-1.

![MiWaveS physical layer LabVIEW user interface (left) and E-band access point node (right) used in first backhaul demonstration activities.](image)

One of the primary goals was to verify the proper integration of all subsystems and characterize the end-to-end system performance in terms of throughput. Figure 5-2 illustrates the measured results.

The peak throughput of the system, in this first implementation, can be reliably achieved at distances up to 100 m which is characteristic for backhaul applications in dense small cell settings. At 1 km distance, a throughput of about 1 Gbit/s can still be guaranteed.

It should be noted that backhaul antennas under development in MiWaveS target higher antenna gains which can help increasing the distance by a factor of >4 and to account for link margins required to operate reliably, e.g., under rain conditions. In general, higher peak throughput in the order of 10 Gbit/s can be achieved by scaling the bandwidth towards 2 GHz and by adding two-fold spatial multiplexing, e.g., by exploiting spatial separation in terms of polarization.
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Figure 5.2. Throughput and frame error rates (FER) measured at different distances and for different modulation-coding schemes in a line-of-sight setup in the E Band at 73.5 GHz. The results have been obtained indoors, using a bandwidth of 750 MHz and 23.5 dBi directive antennas. The distance is varied in a range of 1 m…10 m. [20,40,60] dB mmW attenuators have been added in order to emulate an increase of the physical distance by factors of [10,100,1000] under line-of-sight conditions.

6 Outlook and conclusion

The MiWaveS project achieved a number of major results in its second year, demonstrating the feasibility of mmW access and backhaul technologies for next generation communication systems. In particular, the project transitioned from system concepts to first prototypes and mobile radio access components were developed for V-band, while components for backhauling were developed at V- and E-bands.

The project derived algorithms for the system design at mmW frequencies, such as beam steering, including effective RF codebook design and channel estimation, routing and radio resource management. Several V-band and E-band hardware sub-systems are developed for user equipment devices, access points and backhaul nodes. V-band developments are based on a 65 nm CMOS transceiver chips and focus on integration, efficiency and scalability of transceiver modules with beam-scanning antennas. Other components under study include efficient mmW power amplifiers in V- and E-bands.

The main challenge within the final project year, will be the integration of selected components into a Proof-of-Concept system and the evaluation of its performance. This has already been anticipated by the first milestone targeting backhaul transmission in E-band, using directive antennas. The results show that the system integrating the different components developed by the project provides high performance, both in terms of throughput and covered distance.

7 References


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About MiWaveS

MiWaveS is a collaborative research project, partially funded by the EU FP7 (European Union Framework Programme 7), aiming at developing key enabling technologies for millimetre-wave (mmW) wireless access and backhaul, that will play a key role in the future 5th generation of cellular mobile networks. While mmW is defined as the frequency band between 30 and 300 GHz, the MiWaveS project will focus on communications bands in the V-band (57–66 GHz) and the E-band (71–76 GHz, 81–86 GHz). The MiWaveS project started in January 2014 and will terminate in December 2016.

The MiWaveS’ project is run by a consortium that is composed of the most innovative companies, research centres and academic institutions of Europe. Thanks to the multi-disciplinary expertise of the members, the consortium is strategically positioned to address some key research challenges of future telecommunication systems, as described further down. The strong presence of industrial partners will maximize the impact of the key project outcomes in shaping standards and influencing regulatory bodies, as well as guaranteeing a sound and concrete demonstration of the project results.

The consortium involves partners from eight European countries: Finland, France, Germany, Italy, Spain, Sweden, Switzerland and United Kingdom and comprises fifteen different legal entities, namely three universities (University of Surrey, Technische Universität Dresden and Université de Rennes 1), two research institutes (CEA-Leti and VTT), and nine industrial partners: two telecom operators (France Telecom, Orange and Telecom Italia), two semiconductor and wireless solutions providers (Intel Mobile Communications and ST Microelectronics), one PCB substrate technology provider (Optiprint), and finally four network subsystems, equipment and test platform providers (Nokia, Sivers IMA, TST and National Instruments).

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