Back to Single-carrier for beyond-5G communications above 90 GHz

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Deliverable D3.0

Interface specification

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Executive summary

The work package WP3 in BRAVE has two objectives: 1) integrate the main project's innovations and scenarios into simulation test platforms; and then 2) produce evaluation results for demonstration and dissemination of beyond-5G (B5G) technologies found valuable. This deliverable D3.0, which is edited at the earliest stage of the work package WP3, aims at describing the various models or software blocks that will be interfaced or integrated, as well as the evaluation plan.

The integration and tests rely on two new simulation platforms that will produce the evaluation of our technologies performance in B5G scenarios and under realistic physical conditions.

- A **network design simulator** (S_5GConnect) gathers 3D geographical data, deterministic propagation models and system simulations for the calculation and analysis of KPIs (key performance indicators) related to the 5G mobile access network and last-mile wireless backhaul. It also embeds automatic design features (sites selection and configurations) for the optimization of various kinds of network topologies. The simulator is enriched by the integration of subTHz channel models and modulations developed in BRAVE work package WP2. It is also extended with new indoor capabilities, and new automatic design algorithms devoted to the joint access and wireless backhaul optimization. This simulator will be employed in work package WP3 for the assessment of several networks that operate in the subTHz spectrum: outdoor mesh last-mile backhaul, fixed wireless access (FWA), hotspot, and shopping mall broadband networks.
- A **link budget simulator** gathers or calculates all components of the system link budget, based on the considered scenario (e.g. range, phase noise and propagation conditions) and the system performance indicators (typically BER versus SNR). It facilitates the comparison between different system configurations or techniques; verifies the feasibility with current subTHz transmission technologies, and the respect of existing regulation; and finally, evaluates what would be the power consumption by the proposed system. The link budget simulator is completed with two interfaced link-level simulators, which have been previously developed in work package WP2. They are implementing and assessing MIMO systems (Multiple Inputs Multiple Outputs): first, combined with GSM (Generalized Spatial Multiplexing), and second, based on non-coherent energy detection. Two scenarios will be considered: line-of-sight (LoS) device-to-device (D2D); and kiosk.

The above-mentioned test platforms are integrating four different PHY-layer innovations elaborated in BRAVE work package WP2:

1. The proposed **polar-modulation scheme (P-QAM)** is robust to medium and high phase noise levels, which are expected to affect the subTHz RF chain. The performance of this P-QAM modulation has been evaluated under Gaussian phase noise and additive white gaussian noise (AWGN) channel to produce the SNR-SE mapping tables that relate the achievable spectral efficiencies (SE) to a required signal-to-noise ratio (SNR). Those tables are integrated in the WP3 test platforms, and applied in various scenarios.

2. A **MIMO system with non-coherent modulation and simple energy detection at the receiver** is a convenient way to transport multiple streams and combat the phase noise effect, along with limited complexity. The PHY link-level simulator that was developed in work package WP2 for design of the communication system and preliminary evaluation is extended by plugging a basic ray-tracing channel simulation and realistic antenna radiation patterns. Results will be fed into the link budget simulator, considering a D2D applications.
3. The **Generalized Space Modulation (GSM)** has been identified as a promising solution to reach high spectral efficiency with lower power consumption. The PHY link-level simulator that was used for preliminary assessment of this technology is enhanced in work package WP3: made compliant with ray-tracing channel predictions; comparison of various modulation schemes, including the conventional Spatial Modulation (SM) and alternative Index Modulation approaches (IM). Results will be outputted towards the link budget simulator to capture the performance of such a system in hotspot or D2D scenarios.
4. The assessment of subTHz communication techniques requires the propagation channel to be properly simulated, i.e. with realistic path-loss, departure/arrival angles, frequency response, MIMO properties and adequate relationship with the environment. **Ray-based propagation models** for both outdoor and indoor scenarios have been upgraded for the considered frequencies, for instance with exploitation of a street-level LiDAR point cloud. Those models are employed in work package WP3 in two different ways, either by feeding link-level simulators (described here above) with realistic channel data; or by supporting the evaluation and dimensioning of candidate subTHz network topologies into the network design simulator S_5GConnect.

The proposed subTHz technologies are evaluated on five different B5G scenarios. They are described in D3.0 by their environment, range, mobility, considered antennas, frequency, transmit power, and channelization (typically aggregation of 1 GHz individual channels). The scenarios implemented into the test platforms are as follows:

- Outdoor mesh backhaul *(in the network design simulator)*;
- Fixed Wireless Access *(in the network design simulator)*;
- Shopping mall *(in the network design simulator)*;
- Short-range D2D *(in the link budget simulator)*;
- Kiosk / hotspot *(in both simulators)*.

The integration work will last until the end of year 2020, while the evaluation studies will finish in mid-2021, before being reported in Deliverable D3.1 due in September 2021. Note that many integration tasks have been achieved already; the studies regarding the MIMO energy detection and the outdoor mesh backhaul are under progress today; they will be completed by end of this year.

Table of content

List of Acronyms

5G	5th Generation
5G-NR	5G New Radio
APM	Amplitude Phase Modulation
AWGN	Additive White Gaussian Noise
B5G	Beyond 5G
BER	Bit Error Rate
CPE	Customer Premises Equipment
CPM	Continuous Phase Modulation
D2D	Device to Device
DPSK	Differential Phase Shift Keying
EIRP	Equivalent Isotropic Radiated Power
FEC	Forward Error Correction
FWA	Fixed Wireless Access
GSM	Generalized Spatial Multiplexing
IM	Index Modulation
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging
LoS	Line-of-Sight
MIMO	Multiple Inputs Multiple Outputs
NLoS	Non LoS
OOK	On Off Keying
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PER	Packet Error Rate
PHY-layer	Physical layer
PN	Phase Noise
P-QAM	Polar - Quadrature Amplitude Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadratrure Phase Shift Keying
RF	Radio Frequency
Rx	Receiver / Received
SE	Spectral Efficiency
SM	Spatial Multiplexing
SNR	Signal to Noise Ratio
SubTHz	Sub-TeraHertz
Tx	Transmitter / Transmit
UE	User Equipment
ULA	Uniform Linear Array
URA	Uniform Rectangular Array

1 Introduction

After definition of beyond-5G scenarios and new spectrum opportunities in work-package WP1 of BRAVE project [1] [2], elaboration of new models for the subTHz physical layer [3] and design of adapted efficient waveforms (to be published in later [4]) within work-package WP2, the proposed solutions are demonstrated in work-package WP3.

More precisely, the work-package WP3 has two main goals. First, it consists in integrating the building blocks developed in work-package WP2 for evaluation in a more sophisticated and realistic simulation environment. Second, it must produce evaluation results to assess the feasibility and interest of the proposed solutions and scenarios, but also feed the demonstration and promotion tasks. The wireless systems performance is evaluated based on different metrics: data rate, bit error rate, coverage range, network capacity, and power consumption. Beside those two objectives, it is also expected the results and further developments in work-package WP3 allow for the refinement of the waveforms initially designed in work-package WP2.

This document D3.0 reports about the software integration and evaluation plans, which have been defined at the earliest stage of the work-package. It relies on a precise analysis of the physical layer models and most promising communication systems developed by the partners, as well as their complementarities. It describes how those blocks can be efficiently combined, completed and further tested to reliably assess their performance and build convincing demonstration.

Section 2 explains the methodology that has been followed for the integration and evaluation of the BRAVE innovation features.

Section 3 depicts the main innovations resulting from work-package WP2, which have to be integrated, i.e.

- **Model #1:** Upgraded Volcano model for deterministic simulation of the subTHz propagation channel,
- **Model #2:** SubTHz phase noise model,
- **Innovation #1:** Polar-QAM (Quadrature Amplitude Modulation) scheme robust to strong phase noise,
- **Innovation #2:** Energy detection MIMO (Multiple Input Multiple Output),
- **Innovation #3:** MIMO GSM (Generalized Space Modulation).

Those innovations are implemented either as a data generator (propagation and phase noise models) or a physical-link simulator.

Section 4 introduces the two test platforms that will interface or integrate those innovations, together with the beyond-5G scenarios:

- **Test platform #1: a network design simulator** (S_5GConnect) gathers 3D geographical data, deterministic propagation models and system simulations for the calculation and analysis of KPIs (key performance indicators) related to the 5G mobile access network and last-mile wireless backhaul. It also embeds automatic design features (sites selection and configurations) for the optimization of various kinds of network topologies.

- **Test platform #2: a link budget simulator** gathers or calculates all components of the system link budget, based on the considered scenario (e.g. range, phase noise and propagation conditions) and the system performance indicators (typically BER versus SNR). It facilitates the comparison between different system configurations or techniques; verifies the feasibility with current subTHz transmission technologies, and the respect of existing regulation; and finally, evaluates what would be the power consumption by the proposed system.

The five considered test scenarios are described in section 5:

1. **Scenario #1:** Outdoor mesh backhaul,
2. **Scenario #2:** Fixed Wireless Access (FWA),
3. **Scenario #3:** Shopping mall,
4. **Scenario #4:** Short-range D2D,
5. **Scenario #5:** Kiosk / hotspot.

Finally, section 6 explains how the various blocks (innovations, test platforms and scenarios) are gathered to form the three BRAVE integrated demonstrators:

1. **Demonstrator #1:** MIMO D2D (Device to Device),
2. **Demonstrator #2:** GSM D2D and hotspot,
3. **Demonstrator #3:** Access and backhaul network design.

The shape of those demonstrators can be summarized as in Table 1.

Table 1 : Blocks of the three BRAVE demonstrators.

Demonstrator	Innovations	Models	Test platforms	Scenarios
#1 – MIMO D2D	#2	#1	#2	#4
#2 – GSM D2D	#3	#1, #2	#2	#4, #5
#3 – Network design	#1, #3	#1, #2	#1	#1, #2, #3, #5

Section 7 gives the timeline for the integration and evaluation works until September 2021.

2 Methodology

The schematic of the methodology considered in work-package WP3 is depicted in Figure 2.1. First based on the constraints identified in work-package WP2, few PHY-layer technologies have been identified as potential candidates to address subTHz spectrum requirements. The choice of PHY waveform mainly depends on the target spectral efficiency as well as RF constraints. When phase noise component is high, a non-coherent modulation would be preferred. The complexity of the digital processing, as well as the associated power consumption of devices, are also parameters to take into account.

From a system level perspective, key parameters indicators can be extracted from the PHY-layer model such as throughput versus Signal to Noise Ratio (SNR) for various levels of RF impairment or antenna patterns. Then with the channel prediction and link budget, coverage maps as well as deployment strategies could be discussed or optimized according to various scenarios and optimization criterion.

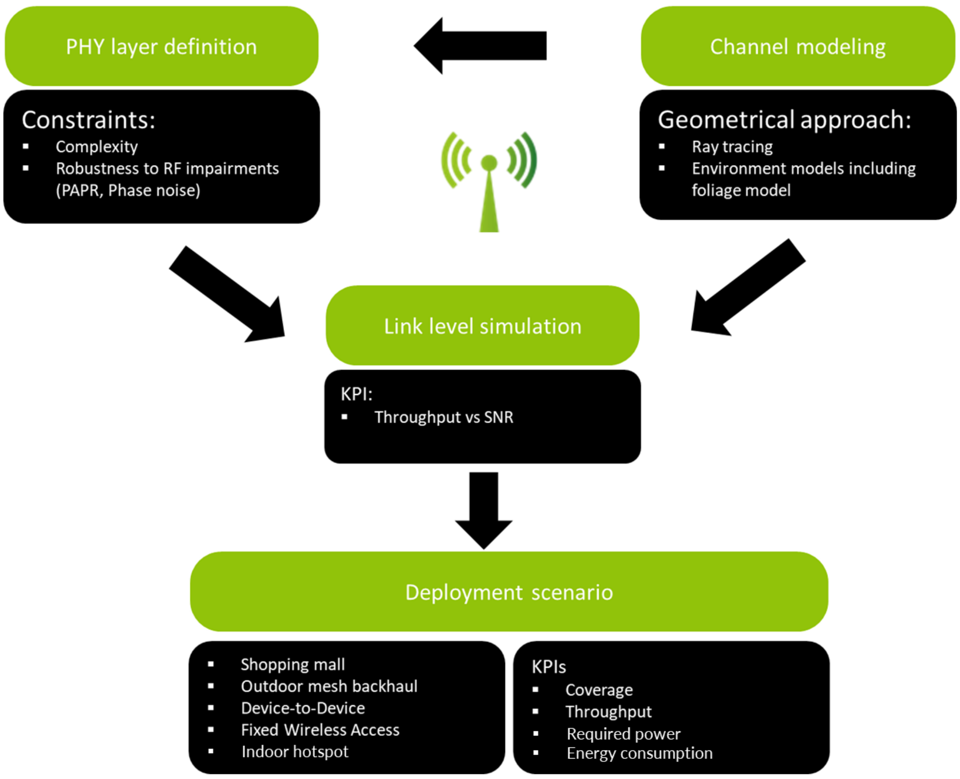


Figure 2.1 – Proposed methodology for end-end evaluation.

3 Modelling of the subTHz Physical-layer

The following tables describe the five main results of work-package WP2 that will be integrated in the demonstration platforms. The description indicates their key benefits, the applicable scenarios and how they will be used in the demonstrations. We can distinguish between two PHY-layer models and three PH-layer technical innovations.

Table 2 : Vocano propagation model (model #1).

Volcano propagation model	
Description	▪ Outdoor & indoor ray-tracing model by SIRADEL. ▪ Extension of the commercial Volcano Urban model, which is today employed for cellular radio-planning or propagation channel simulations up to 90 GHz. ▪ Extension up to 200 GHz, with extrapolated material properties, increased losses. ▪ Support for highly detailed geographical digital environment (LiDAR point cloud, urban furniture, indoor furniture…). ▪ [3], section 2.
Implementation details	▪ Available as a compiled library. ▪ Integrated in S_5GConnect software.
Expected usage in BRAVE WP3 studies	▪ Generation of realistic path-loss values, MIMO coefficients or other wideband channel properties, for assessment of proposed BRAVE waveform/modulation schemes in link-level simulators. ▪ Prediction of the propagation data for evaluation of subTHz network deployments e.g. optimal topologies or inter-site distance.
Key benefits	▪ Performance assessment and demonstration of the proposed PHY solutions and applications from very realistic propagation data.
Applicable scenarios	▪ Mobile access for outdoor or indoor hotspot areas. ▪ Last-mile backhaul (backhaul/fronthaul). ▪ FWA.

Table 3 : Phase Noise (model #2).

SubTHz phase noise model	
Description	▪ Strong phase impairments due to the poor performance of high-frequency oscillators. ▪ Impact of PN on received symbols by a zero-mean Gaussian distribution. ▪ [3], section 3.
Implementation details	▪ Analytical formulation: Gaussian noise in phase domain. ▪ Three different levels: none, medium (with noise floor -110 dB for 1 GHz channel), and high (-100 dB).
Expected usage in BRAVE WP3 studies	▪ Consideration of medium or high PN levels in all PHY simulations and network demonstrations.
Key benefits	▪ Performance assessment and demonstration of the proposed PHY solutions and applications based on realistic RF chain impairments.
Applicable scenarios	▪ All.

Table 4 : Polar-QAM modulation (innovation #1).

Polar-QAM modulation	
Description	▪ Optimized modulation scheme achieving robustness over PN channels. ▪ Modulation points are distributed on circles. ▪ Modulation parameters are adapted vs. PN level and SNR. ▪ [6] [3], section 4.
Details	▪ Implemented in a PHY simulator including FEC, and Phase noise channel model. ▪ Available as a compiled Matlab function. ▪ Supported configurations: o Phase noise: low, medium, strong. o QAM modulations: QPSK up to 256QAM. o P-QAM modulations: up to 6 bits per symbol. o FEC: 5G-NR LDPC. ▪ Extraction of PER vs SNR tables.
Expected usage in BRAVE WP3 studies	▪ Consideration of subTHz PN constraints. ▪ Estimation of the link budget, expected coverage, throughput and system power consumption, based on different PN models. ▪ Production of PER vs SNR to be integrated into network simulations. ▪ Through code share, performance comparison of different modulations can be easily performed.
Key benefits	▪ Elaboration of high-data-rate subTHz systems.
Applicable scenarios	▪ Backhaul/fronthaul.

Table 5 : Energy detection (innovation #2).

Energy detection (ED) MIMO	
Description	▪ Combining spatial multiplexing with Energy detection (ED) receivers for together high-data-rate and PN robustness. ▪ Each spatial stream transmitted with a directive antenna on a LoS channel
Implementation details	▪ Implemented in a PHY-layer link simulator including non-coherent detection and MIMO quadratic receiver. ▪ Available as a compiled Matlab function. ▪ Extraction of PER vs SNR tables.
Expected usage in BRAVE WP3 studies	▪ Estimation of the link budget, expected coverage, throughput and system power consumption. ▪ Production of PER vs SNR to be integrated into network simulations.
Key benefits	▪ Elaboration of low-complexity low-power subTHz systems.
Applicable scenarios	▪ Kiosk. ▪ D2D.

Table 6 : MIMO GSM (innovation #3).

MIMO GSM (Generalized Space Modulation)	
Description	▪ GSM: Index Modulation (IM) using the spatial domain as the index. ▪ Spatial multiplexing of different symbols simultaneously like in conventional MIMO systems, but from the selection of a subset of transmit antennas.

Implementation details	▪ Implemented in a PHY-layer link simulator including non-coherent detection and MIMO transceiver.
	▪ Supported configurations:
	    o MIMO setups with\without Rx diversity: SM, GSM
	    o Phase noise: low, medium, strong.
	    o Modulations : QAM, P-QAM, DPSK.
	    o GSM mode: Conventional GSM, Enhanced GSM (Adaptive)
	▪ Extraction of BER vs SNR tables.

Expected usage in BRAVE WP3 studies	▪ Estimation of the link budget, expected coverage, throughput and system power consumption. ▪ Production of PER vs SNR to be integrated into network simulations.
Key benefits	▪ Elaboration of subTHz systems with high spectral efficiency, under power consumption constraints.
Applicable scenarios	▪ Kiosk. ▪ D2D. ▪ All scenarios suitable for MIMO communication.

4 Test platforms

4.1 S_5GConnect: Network design simulator

Facing new challenges with the rise of 5G, the coming of 6G and a growing level of densification, telecom operators are looking for efficient network planning solutions to guarantee best quality service to their customers, in any type of environment and configurations. In that perspective, Siradel provides comprehensive solutions, combining 3D digital maps, advanced propagation models (leading radio propagation model, Volcano) and simulation software to optimize any network planning and deployment, including 5G, FWA, IoT, etc.

Used worldwide by several stakeholders in the telecom sector, Siradel radio planning software **S_5GConnect** help telecom operators and regulators, equipment manufacturers and utilities as well as infrastructure managers address current and future connectivity challenges with powerful 3D tools. BRAVE demonstrations and design assessments will be conducted in a prototype version of S_5GConnect used a test platform.

The S_5GConnect software embeds the deterministic in-house Volcano model. Based on our 25 years' experience in geodata production and radio engineering, Volcano is one of the leading 5G propagation models combining high accuracy at the best computation speed, with recognized robustness and reliability to cope with operational environments. Volcano is computing multiple propagation paths based on the ray theory and UTD approximation, for any kind of environments i.e. including rural, urban, campus and indoor [5]. Volcano is providing enhanced vegetation discrimination, as required in millimeter and above frequencies [3]. Use of LiDAR point cloud data offers the necessary level of details regarding foliage representation which enables users to obtain highly-accurate and realistic propagation under, through and above tree branches and foliage.

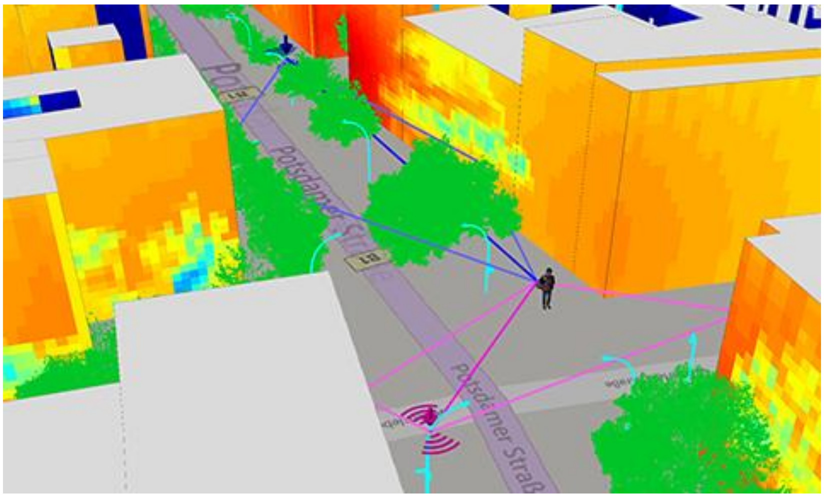


Figure 1 : S_5GConnect test platform – Point-to-Point prediction & FWA along-façade coverage.

In addition to advanced vegetation discrimination, the Volcano version released in late 2019 has improved its computation time by more than 80% in presence of highly detailed point cloud data.

With this optimized ray tracing calculation method, the BRAVE partners will be able to run accurate subTHz coverage predictions in no more than a few tens of minutes.

S_5GConnect simulates with maximum accuracy several wireless link technologies (mobile access, FWA, and wireless backhaul) at various frequencies (sub6GHz, 6-42GHz and millimeter waves) and any link visibility (LoS, nLoS and NLoS). Typical simulation outputs are: RSRP, RSSI, SINR, and throughput, either computed at a particular link, or from a multi-link network, or from over a coverage map.

The calculation methodology can be briefly summarized as follows:

1. Prediction of propagation losses and multi-paths.
2. Application of the antenna radiation mask (possibly with beamforming or automatic antenna alignment).
3. Computation of the interference and SINR.
4. Mapping to the spectral efficiency and throughput.

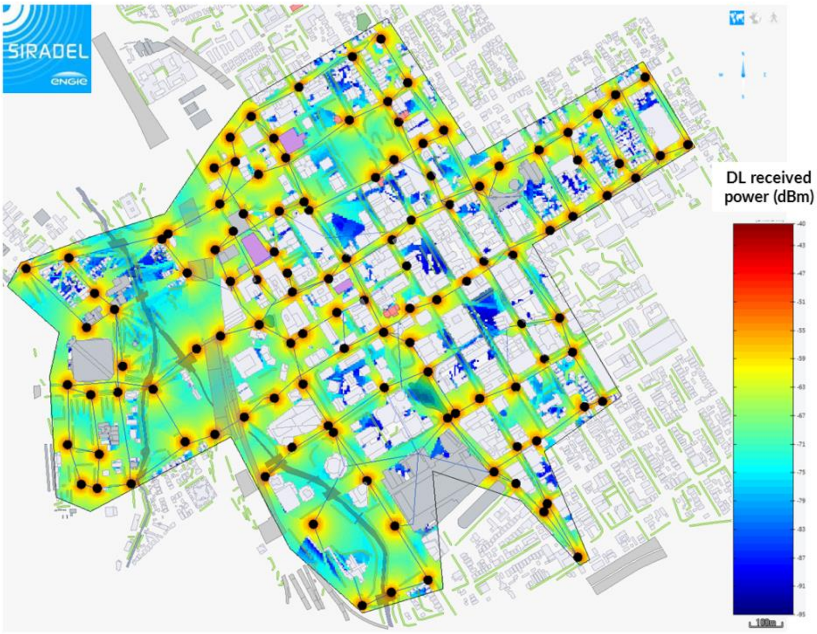


Figure 2 : S_5GConnect test platform – Design of a wireless mesh backhaul network.

S_5GConnect relies on a 3D engine that allows the user to visualize the geodata along with the simulation results, easily navigate and analyse the radio conditions. In particular, the display of LiDAR point cloud is permitted. The software supports several geodata formats that are employed in the radio-planning world (Shape, MapInfo, DXF …). In particular, for the BRAVE project studies, the geodata will be directly provided by SIRADEL.

S_5GConnect is today devoted to outdoor network design, but will soon integrate indoor capabilities, which will be exploited for BRAVE investigations.

S_5GConnect is providing several solutions for automated network design, which are applicable to various scenarios e.g. small-cell network, point-to-point backhaul, or FWA. Automated design consists in the optimization of the physical infrastructure and site configuration, along with minimization of the cost, and achievement of a given connectivity target typically a ratio of connected user terminals. Such solution will serve the BRAVE demonstration by assessing what network density is required for providing a particular service.

Following integrations will be part of the BRAVE work-package WP3 activities:

- Volcano propagation model at subTHz frequencies *(software integration)*;
- Mapping tables from subTHz modulations *(project's configuration)*;
- BRAVE scenarios *(project's configuration)*;
- Automated design for target BRAVE topologies, e.g. for joined wireless backhaul and access optimization *(software integration or interface)*.

Simulations will be run from the S_5GConnect GUI, but could be as well driven from an external batch or a Matlab script if more relevant.

4.2 Link budget simulator

Different tools are prepared in Excel sheets to allow evaluating quickly the tested systems. The tools are listed in the following:

- Achievable Signal-to-Noise Ratio (SNR) estimator according to scenario parameters.
- Data rate estimator with channel aggregation and/or bounding based on achievable system spectral efficiency at the achievable SNR.
- Link budget and power consumption estimator based on the required SNR to achieve a target performance.

The first tool is to estimate the achievable SNR based on RF properties (antenna gain, cable losses, available transmit power, etc…), environment and channel characteristics (Tx-Rx separation distance, losses, …). This tool can be configured to deduce the realistic achievable SNR for any scenario by updating the different parameters highlighted in Figure 3 while taking into consideration the recent values in current technology suitable for the studied scenario. For example, the achievable SNR for a downlink indoor scenario (Kiosk, D2D, office hotspot) is 20.19 dB using the parameters in Figure 3 when the distance between transceivers is 8 m and a 0 dB UE antenna gain is considered.

Achievable SNR estimation		
Fill Parameters in yellow to deduce achievable SNR NB: All parameters in grey are calculated automatically		
Parameter Name	**Value**	**Parameter symbol and equations**
Carrier frequency (GHz)	145.00	fc
Distance (m)	8.00	d
Bandwidth (GHz)	1.00	BW
Transmit Power (dBm)	14.00	Pt
Transmit antenna gain (dBi)	25.00	Gt
Tx Losses	1.00	Ltx
EIRP (dB)	38.00	EIRP=Pt+Gt-Ltx
Free space propagation loss (dB)	93.74	fspl=20 log(4pi*d*fc/c)
Other losses (gas attenuation,shadowing, fading,...)	0.00	Lchannel
Total Channel losses	93.74	Lchannel_total
Rx losses	1.00	Lrx
Receive antenna gain (dBi)	0.00	Gr
Rx Signal Level (dBm)	-56.74	RSL=EIRP-Lchannel_total-Lrx+Gr
Thermal noise(dBm)	-83.93	Nthermal
Noise figure	7.00	NF
Noise floor	-76.93	Noise floor= NF+Nthermal
Achievable SNR (dB)	**20.19**	SNR=RSL-Noise floor

Figure 3 : Excel Sheet for achievable SNR estimator.

The second tool calculates the maximum data rate according to the system spectral efficiency (Figure 4). This spectral efficiency should consider the achievable SNR of the studied scenario and the required system performance. In addition, the data rates are deduced if channel bounding and/or aggregation is used. Two different total bandwidths are considered in this tool:

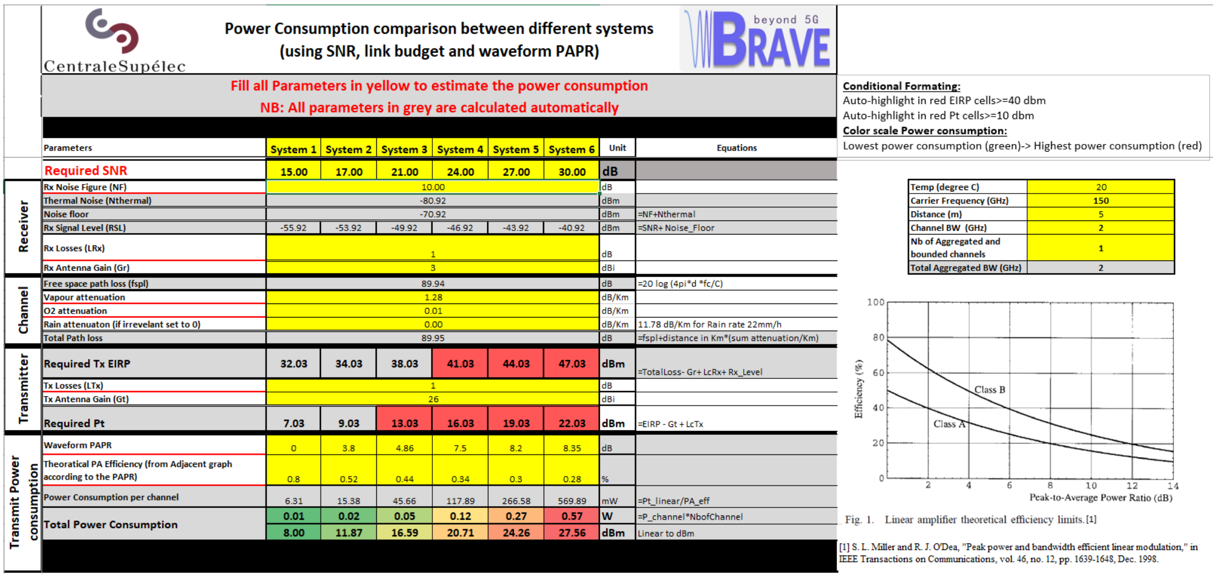
- Up to 12.5 GHz by channel bounding of equal channel bands, this total bandwidth is available around the 157.75 GHz.
- Up to 58.6 GHz by channel bounding and aggregation of equal channel bands, this total bandwidth is available between 90 GHz and 200 GHz.

Data rate with channel bounding and aggregation (using system spectral efficiency)			
Fill Parameters in yellow to deduce data rate			
Channel Bandwidth (GHz)	2.00		
Percentage of usefull BW	0.83		
System Spectral efficiency	12.00		
Data rate per channel (Gbps/channel)	**20.00**	**Nb of Channels**	**Total Aggregated BW (GHz)**
Data rate with channel bounding (up to 12.5 GHz) around 157.75 GHz	**120.00**	**6.00**	**12.00**
Data rate with channel aggregation and bounding (up to 58.6 GHz) of equal channel bands between 90 GHz and 200 GHz	**500.00**	**25.00**	**50.00**

Figure 4 : Excel Sheet for data rate estimation with channel bounding and/or aggregation.

The last tool prepared in Excel sheet depicted in Figure 6 estimates the required transmit power and Effective Isotropic Radiated Power (EIRP) according to the link budget and the required SNR to achieve the target BER performance. Moreover, this tool allows to roughly estimate the power consumption while taking into consideration the Peak-to-Average Power Ratio (PAPR) of the transmitted waveform that affects the Power Amplifier (PA). This tool estimates these parameters simultaneously for several systems (up to 6) under same conditions by using their required SNR that allows them to achieve same performance and spectral efficiency, and thus it allows the comparison of the following factors:

- System Link budget.
- Feasibility of required transmit power in current technology which is in order of 10 dBm.
- Respect to subTHz regulations and standard concerning EIRP (maximum EIRP is 40 dBm).
- System power consumption.



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Power Consumption comparison between different systems
(using SNR, link budget and waveform PAPR)

Fill all Parameters in yellow to estimate the power consumption
NB: All parameters in grey are calculated automatically

	Parameters	System 1	System 2	System 3	System 4	System 5	System 6	Unit	Equations
	Required SNR	15.00	17.00	21.00	24.00	27.00	30.00	dB	
Receiver	Rx Noise Figure (NF)	10.00						dB	
	Thermal Noise (Nthermal)	-80.92						dBm	
	Noise floor	-70.92						dBm	=NF+Nthermal
	Rx Signal Level (RSL)	-55.92	-53.92	-49.92	-46.92	-43.92	-40.92	dBm	=SNR+ Noise_Floor
	Rx Losses (LRx)	1						dB	
	Rx Antenna Gain (Gr)	3						dBi	
Channel	Free space path loss (fspl)	89.94						dB	=20 log (4pi*d *fc/C)
	Vapour attenuation	1.28						dB/Km	
	O2 attenuation	0.01						dB/Km	
	Rain attenuaton (if irrevelant set to 0)	0.00						dB/Km	11.78 dB/Km for Rain rate 22mm/h
	Total Path loss	89.95						dB	=fspl+distance in Km*(sum attenuation/Km)
Transmitter	Required Tx EIRP	32.03	34.03	38.03	41.03	44.03	47.03	dBm	=TotalLoss- Gr+ LcRx+ Rx_Level
	Tx Losses (LTx)	1						dB	
	Tx Antenna Gain (Gt)	26						dBi	
	Required Pt	7.03	9.03	13.03	16.03	19.03	22.03	dBm	=EIRP - Gt + LcTx
Transmit Power consumption	Waveform PAPR	0	3.8	4.86	7.5	8.2	8.35	dB	
	Theoratical PA Efficiency (from Adjacent graph according to the PAPR)	0.8	0.52	0.44	0.34	0.3	0.28	%	
	Power Consumption per channel	6.31	15.38	45.66	117.89	266.58	569.89	mW	=Pt_linear/PA_eff
	Total Power Consumption	0.01	0.02	0.05	0.12	0.27	0.57	W	=P_channel*NbofChannel
		8.00	11.87	16.59	20.71	24.26	27.56	dBm	Linear to dBm

Conditional Formating:
Auto-highlight in red EIRP cells>=40 dbm
Auto-highlight in red Pt cells>=10 dbm
Color scale Power consumption:
Lowest power consumption (green)-> Highest power consumption (red)

Temp (degree C)	20
Carrier Frequency (GHz)	150
Distance (m)	5
Channel BW (GHz)	2
Nb of Aggregated and bounded channels	1
Total Aggregated BW (GHz)	2

Fig. 1. Linear amplifier theoretical efficiency limits.[1]

[1] S. L. Miller and R. J. O'Dea, "Peak power and bandwidth efficient linear modulation," in IEEE Transactions on Communications, vol. 46, no. 12, pp. 1639-1648, Dec. 1998.

Figure 5 : Excel Sheet for link budget and power comparison estimation.

All those tools require to fill the input parameters in the excel sheet (highlighted in yellow in Figure 3 to Figure 5) according to the considered scenario and system configuration. Then, the tool calculates the needed information accordingly. The last tool (Figure 5) automatically highlights not-allowed or not-feasible values:

- The required Transmit Power (Pt) exceeds 10 dBm.
- The required EIRP exceeds 40 dBm.
- The total power consumption is mapped to a colour scale from green (lowest) to red (highest).

5 Evaluation scenarios

The five considered scenarios are described in following sub-sections.

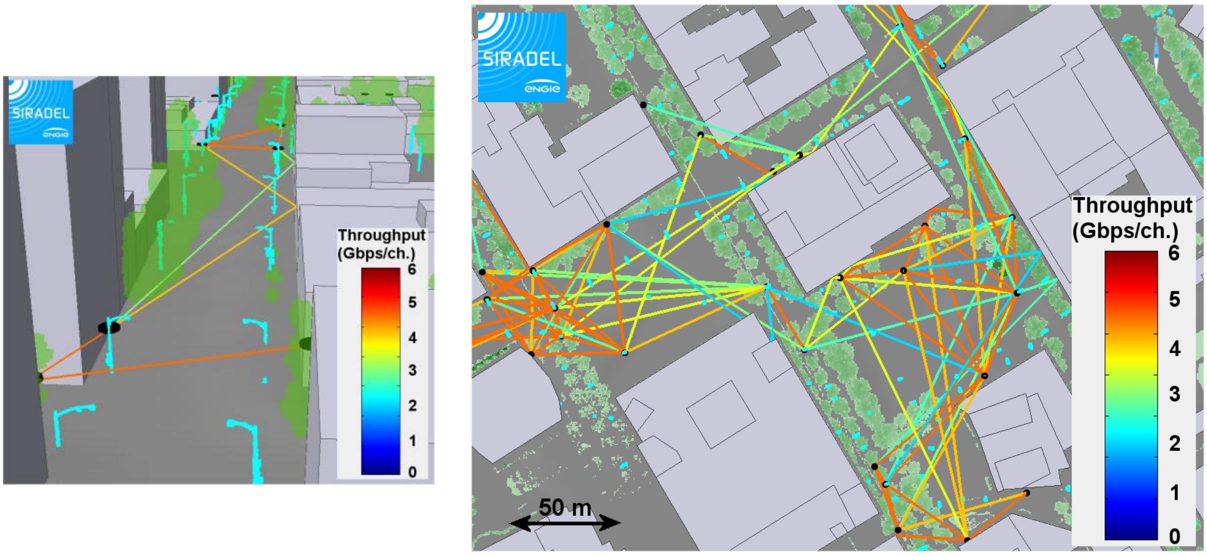
5.1 Outdoor mesh backhaul

The outdoor Multi-Gbps wireless backhaul solution will be studied and demonstrated in two different environments: a dense urban area with high vegetation density, i.e. San José city centre, as shown in Figure 6; and an industrial campus composed of a few streets having trees and bordered by office or apartment buildings, as shown in Figure 7. The subTHz nodes are fixed and supposed to be installed on lampposts, or possibly on a building façade or a low rooftop.

Antennas are supposed to be highly directive and perfectly aligned. A medium transmit power is considered, i.e. around 1 W. Frequency is 150 GHz. Channel bandwidth is 1 GHz, while channel aggregation over several tens of GHz is supposed possible.

The outdoor ray-tracing subTHz model is coupled with the P-QAM modulation scheme developed in WP2 in order to simulate the link achievable throughputs, under medium PN level.

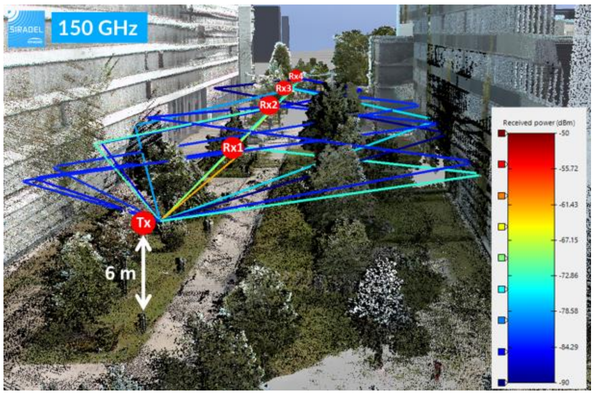
Several candidate positions will be identified in each environment; they will be used as inputs when running an optimization design process where both the mobile access (at a lower frequency) and the backhaul layer will be predicted. Objective will be first, to demonstrate the ability of the subTHz technologies to deliver ultra-high data rate with sufficient protection over the backhaul layer, and second, to assess the required backhaul dimension for particular targets in the access network (i.e. capacity, coverage, …).



(a) Dominant propagation paths (b) Mesh link throughputs

Figure 6 : Illustration of San José downtown scenario for subTHz mesh backhaul studies.

(a) Top view



(b) Propagation multi-paths between mesh backhaul nodes

Figure 7 : Illustration of the industrial campus scenario for subTHz mesh backhaul studies

5.2 Fixed Wireless Access

The Fixed Wireless Access (FWA) scenario will be assessed in a suburban North-American environment. The considered network is composed of subTHz access points located on urban furniture (dedicated poles, lampposts) or low rooftops with a beamforming antenna. The whole sector covered by the antenna is 120°, but each individual link is taking benefit of the higher gain offered by directive beams. The user terminals or CPE's (Customer Premise Equipment) are fixed antennas installed on the façade or rooftop of the buildings and houses, with as well beamforming capabilities. The alignment between the antenna beams is supposed to be automatic, i.e. based on dedicated signals and communication protocol.

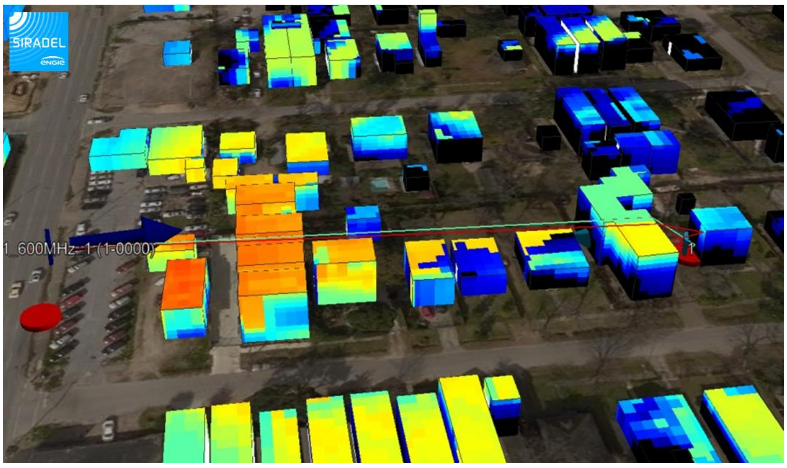


Figure 8 : Example of a FWA prediction map.

A medium transmit power is considered for downlink, i.e. around 1 W. Frequency is 150 GHz. Channel bandwidth is 1 GHz, while channel aggregation over several tens of GHz is supposed possible.

The outdoor ray-tracing subTHz model is coupled with the P-QAM modulation scheme developed in work-package WP2 in order to simulate the link achievable throughputs, under medium PN level.

First, this scenario will be employed to assess the cover range of a FWA access point (under minimum throughput constraint) and the number of reachable customers (considering the maximum cell capacity). Second, the required density of FWA access points will be estimated by automatic network design.

This study will rely on 3D predictions, as shown in Figure 8, in order to reproduce all possible CPE locations.

5.3 Shopping mall

The subTHz transport network could also be deployed as a complement to the optical fiber inside large venues, e.g. airports, railway stations, stadium, campus, or commercial halls. While the optical fiber is distributing strong capacity in the different blocks of the venue, the wireless mesh backhaul may be the final link to some fixed, portable or even mobile (e.g.. flying) access points. If combined with efficient auto-alignment and dynamic routing algorithms, the subTHz transport layer can adapt to changes e.g. related to densification, maintenance, event, or construction works.

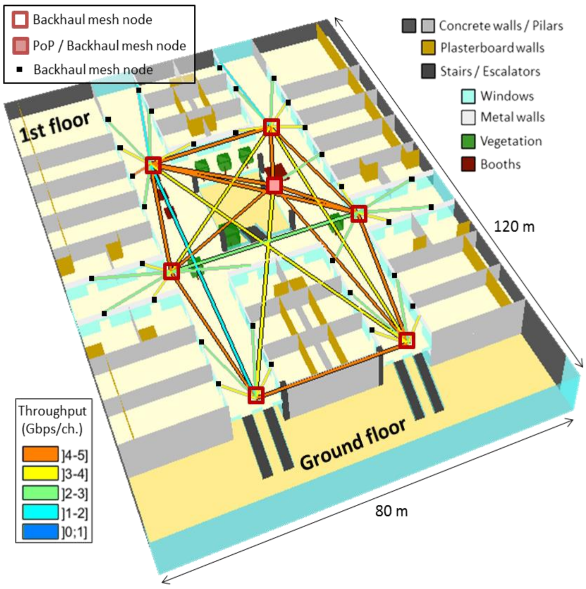


Figure 9 : Deployment of a subTHz backhaul within a shopping mall environment.

The strong obstruction losses oblige the subTHz hops to be deployed in a clear space, typically in large rooms or open areas, above most furniture and bodies. Fiber relays can be used to extend the network coverage to another room.

The evaluation study will be carried out in a model of commercial hall. Figure 9 shows the two-floor 120m×80m building, which is composed of a large entrance area, large alleys with few obstacles (booths, vegetation, and pillars), and a succession of shops. Each floor is five meters high. A mesh subTHz network will be demonstrated, which is able to feed several wireless access points distributed into the building. Two different kinds of access points are considered: those inside the shops, which require a subTHz relay to be positioned on the outer surface of the shop window; and those connected to a portable/mobile subTHz relay installed in the main corridors.

Antennas are supposed to be highly directive and perfectly aligned. A medium transmit power is considered, i.e. around 1 W. Frequency is 150 GHz. Channel bandwidth is 1 GHz, while channel aggregation over several tens of GHz is supposed possible.

The indoor ray-tracing subTHz model is coupled with the P-QAM modulation scheme developed in WP2 in order to simulate the link achievable throughputs, under medium PN level.

5.4 Short-range D2D

Multi Gbps short-range communications can be utilized for many consumer electronic applications such as High speed file transfer or wireless connector. First concepts have been proposed in the V-Band. Basically, simple modulation (OOK) and envelope detection are used over the entire available bandwidth. Moving to subTHz band gives extra bandwidth and therefore more throughput. For this application, we also study the benefits of considering spatial multiplexing when it is combined with envelope detector. We assume short range device-to-device communication (up to 5m) in an indoor environment with directive antenna, line-of-sight condition and very limited RF power. Channel model is derived with a simple geometrical approach. Co channel interference is also taken into the propagation model.

5.5 Kiosk / Hotspot

Kiosk and hotspot scenarios are evaluated based on MIMO radio channels predicted in the office environment already considered in WP2 propagation studies [3]. Radio channel samples have been computed with the indoor subTHz ray-tracing at 150 GHz, for 10 different access point positions (Figure 10) and 50 user terminal locations. Both LoS and NLoS situations are met. An antenna array is supposed at each access point, either of ULA (uniform Linear array) or URA (uniform rectangular array) shape, with dual-polar radiation elements. A dual-polar antenna is simulated as well at the user terminal.

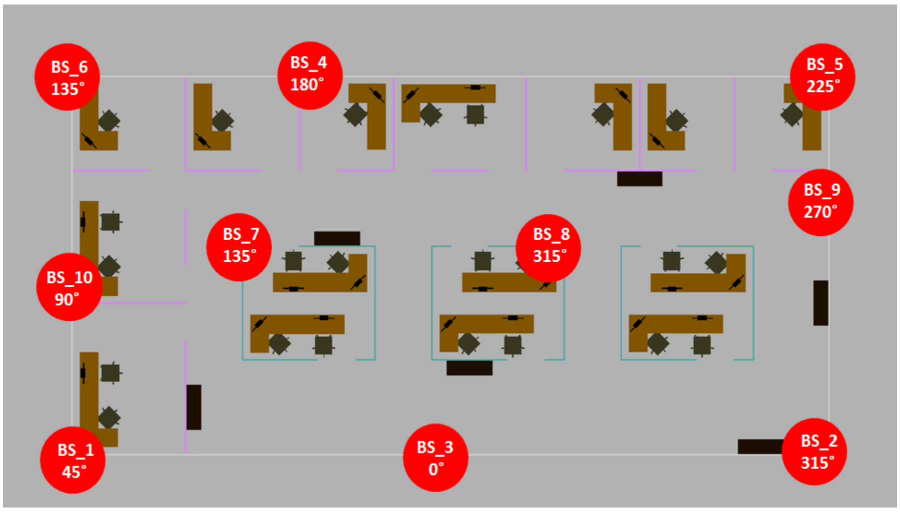


Figure 10 : Considered in-office scenario with location of all tested access points.

All the channel samples have been made available in a kind of Matlab database, and will be completed during the WP3 work period, depending on new requirements.

Each test scenario for kiosk or hotspot evaluation will pick the needed samples from the database. For instance, the kiosk performance will be assessed from samples having a Tx-Rx range below 8 meters.

6 Integration & evaluation plan

This section explains how the different blocks are combined in order to form the three BRAVE demonstrators.

6.1 Demonstrator #1: MIMO D2D

This demonstrator is basically composed of the MIMO D2D link-level and link-budget simulators. The integration of signal processing dedicated to MIMO energy detection receivers, link budget as well as propagation models will give KPIs including, throughput, required transmitted power, and form factor.

The channel matric is modelled from a simple ray-tracing model, assuming LoS. The channel model also integrates real antenna pattern measured in the D-band.

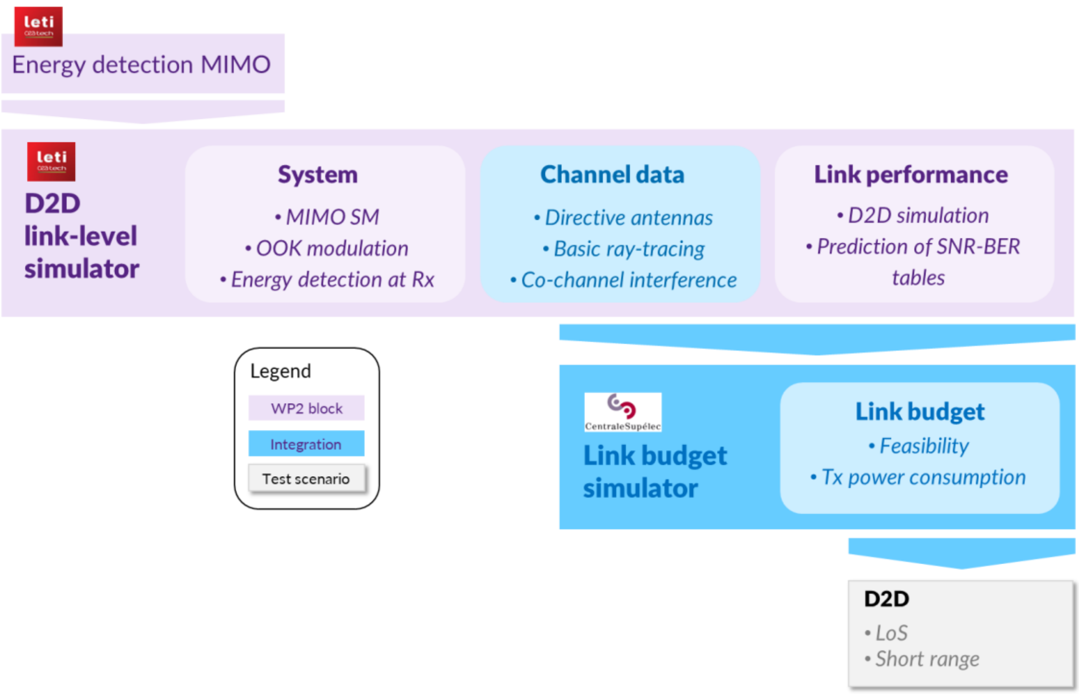


Figure 11 : Integration diagram for the MIMO D2D demonstrator.

6.2 Demonstrator #2: GSM D2D and hotspot

GSM modulation performance will be evaluated in highly correlated channels, based on indicators such as BER, required SNR achieving Tbps, required transmit power, average PAPR & power consumption tables. It will include numerical comparison between several APM-GSM systems that employs different APM schemes as: PSK, DPSK, CPM, QAM, and Polar-QAM. The performance analysis will be extended to the consideration of impairments like the phase noise (low, medium, and High) in the subTHz channels using ULA and URA array geometry. Analysis will be extended with evaluation of GSM-IM using real ray-tracing channel data in-office scenario environment with AP-UE distance between 2 and 8 meters (mean distance is 5 m). Last, the performance assessment using GSM scheme from the link budget will be provided under excel sheet format.

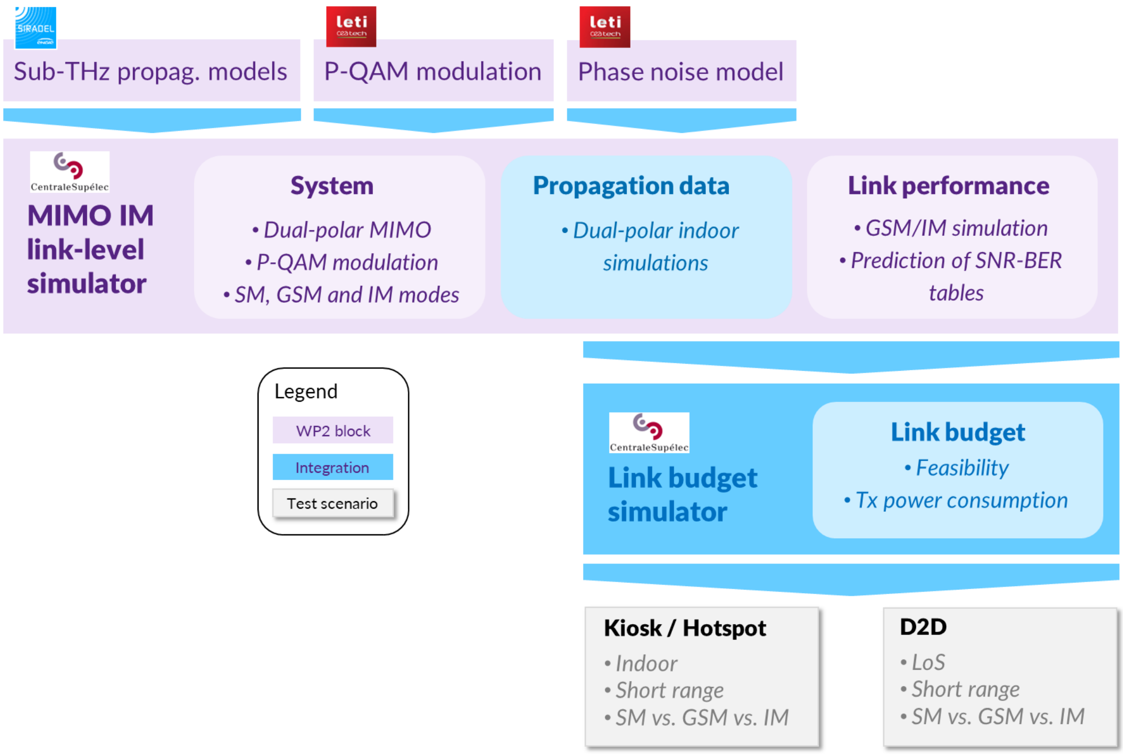


Figure 12 : Integration diagram for GSM D2D and hostpot.

6.3 Demonstrator #3: Access and backhaul Network design

This demonstrator is basically obtained by the integration of subTHz indoor/outdoor ray-tracing channel models and subTHz modulation scheme performance into the network design tool S_5GConnect. Several topologies can be tested and automatically optimized in realistic digital environments in order to dimension and evaluate the performance of multi-node subTHz systems. Both wireless access and backhaul layers will be considered. Their design will possibly be jointly optimized thanks to the implementation of a new automated module.

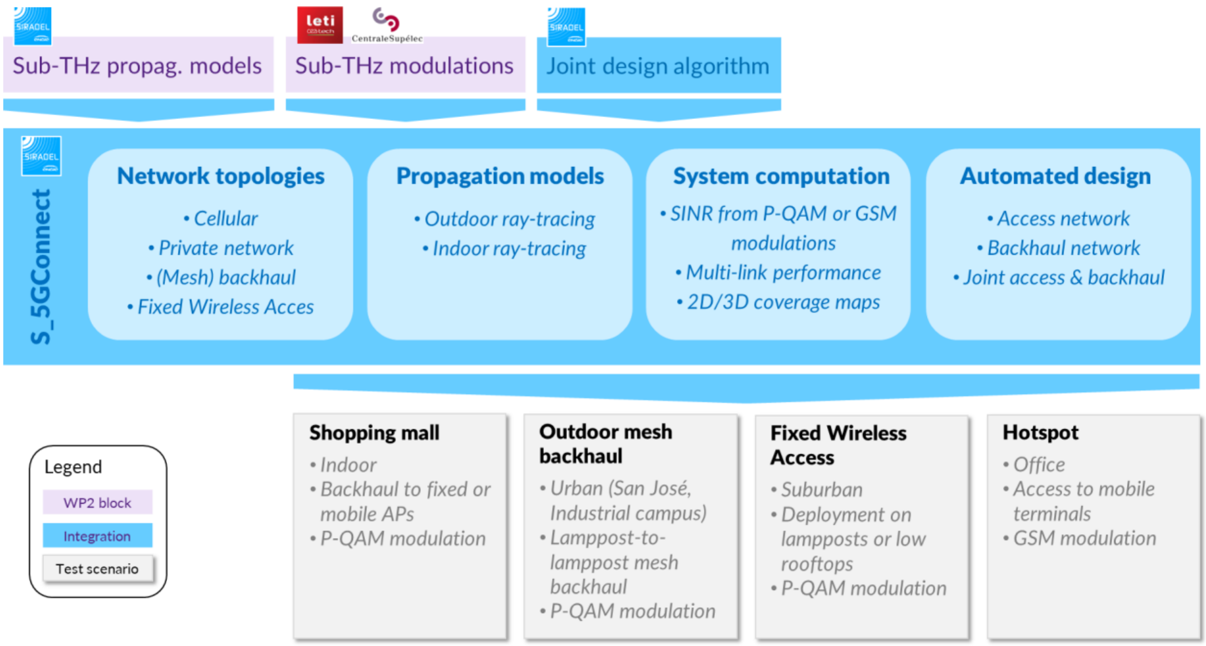


Figure 13 : Integration diagram for Access and backhaul network design.

7 Roadmap

The integration tasks for elaboration of the three demonstrators have been started in 2019 and will be completed at the end of year 2020.

They will permit for various simulation studies and demonstrations until mid-2021.

Finally, all results will be reported in Deliverable D3.1 to be published in September 2021.

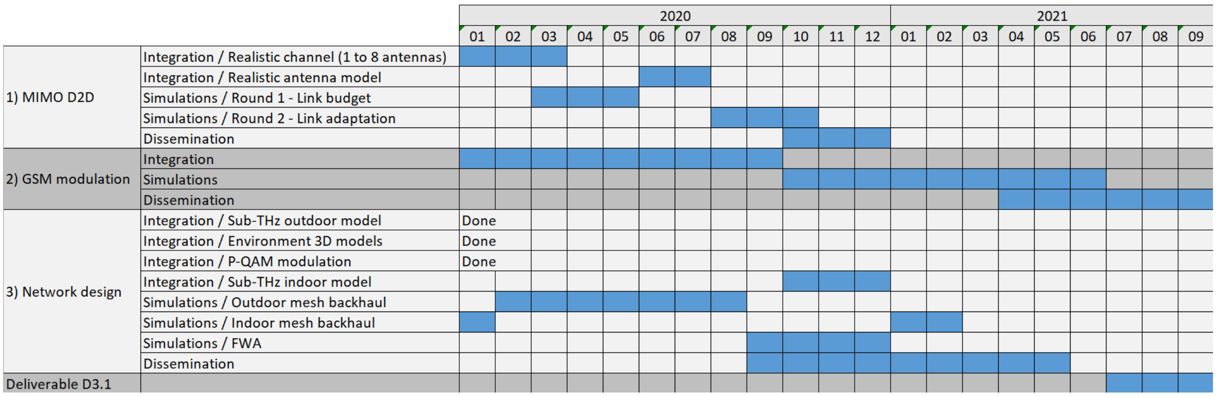


Figure 14 : WP3 roadmap.

8 Conclusion

The BRAVE partners are integrating the PHY-layer models and subTHz waveforms elaborated in work-package WP2 in order to evaluate their performance in realistic conditions (geographical environment, network topology, RF chain impairments) and for different applications such as hotspot access network, fixed access network, backhauling and device-to-device. This work will permit to assess and possibly compare different configurations and deployment scenarios, and will therefore complete the analysis started in WP2. It will also demonstrate the capabilities of the proposed technologies e.g. in terms of capacity and data rate. The feasibility will be studied by considering the required complexity, transmit power, energy consumption and deployment strategies.

This deliverable D3.0 has described the different blocks that are integrated into the BRAVE demonstrators, i.e. the PHY-layer models, PHY-layers technologies, simulators and scenarios. The integration is today under progress, and already permits for the first simulations to be run. The demonstration results will be disseminated in second half of year 2020 until the end of the project in September 2021.

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