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Multi-objective optimisation of human exposure for various 5G network topologies in Switzerland

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ABSTRACT

The constant increase in the required user capacity and the evolution of wireless network technologies impact the exposure that users experience from wireless networks. This paper evaluates various 5G network topologies regarding human exposure, mobile communication quality, and sustainability. We assess human exposure, based on a novel Exposure Ratio (ER) metric, in 5G networks that include Massive Multiple-Input Multiple-Output (MaMIMO) and compare them with existing 4G deployments in three environments in Switzerland. The quality and sustainability of mobile communication are evaluated by extrapolating data rates from mobile operators to the year 2030. A multi-objective optimisation algorithm is implemented to design the 5G network topologies, maximising the user coverage while minimising the downlink (DL) and uplink (UL) exposure. An extensive set of simulations investigated three municipalities, three operators plus one unified network, three use cases (UL/DL data rates), three scenarios (indoor and outdoor coverage), and two optimisation methods. The study results confirm that the human exposure in a 5G network is dominated by the UL being ten times larger than the DL exposure. Furthermore, comparing a 5G deployment with 10 times the traffic capacity of a real 4G network, DL exposure increases by 36% on average, and UL exposure decreases by up to 75% depending on the scenario. Regarding indoor coverage versus outdoor only, our results show that DL exposure can be reduced by a factor of 10 if only outdoor coverage is targeted. Finally, the study concludes that from the human exposure perspective, the ideal network should use 5G MaMIMO and be optimised for both UL and DL exposure.

1. Introduction

The usage of network planning tools has been crucial to determine optimal cellular network deployments under diverse constraints. In 5G networks, massive multiple-input multiple-output (MaMIMO) proposes several advantages related to spectral and energy efficiency, by focussing the energy of the antenna in a specific direction where users are located [1]. However, the concentrated energy of the beams formed in MaMIMO leads of regions with higher power density [2]. These two aspects, the direction of beams and the spatial concentration of energy, pose a burden for 5G network planning, compared with traditional 2G, 3G and 4G planning, as they will need a broad knowledge of the environment to identify the maximum transmitted power that comply with safety limits [3].

The following study investigates various 5G network topologies in diverse city environments around Switzerland with a main focus on the human exposure optimisation. Here, mobile communication quality and future sustainability are defined as minimum coverage and more appropriated datarate network constraints to be satisfied by the network planner. To achieve this goal, the following key aspects will be evaluated: (i) The exposure for different network technologies based on 4G and 5G networks will be compared; (ii) The impact of the separation of indoor and outdoor coverage on human exposure; (iii) The effect of a unified mobile network, which is the sum of all base station (BS) locations from all three independent networks compared with them independently; (iv) The effect of adaptive (MaMIMO) antennas on the spatial exposure distribution and data rates, and (v) The network size to satisfy network quality and sustainability requirements.

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In this work, we consider multi-operator, multifrequency, multi-technology scenarios under diverse exposure and network constraints. These scenarios use realistic 3D models of both urban and suburban cities in Switzerland, accounting for realistic propagation environments. To our knowledge, there is no complete study on the planning of the entire 4G and 5G network with adaptive antennas that consider human exposure both in the uplink and in the downlink.

The main innovations in this paper are as follows.

- The definition of the Exposure Ratio (ER), that enables an easy comparison of human exposure for Multi-technology and multi-frequency networks.
- An ER study based on the uplink (UL) and downlink (DL) time averaged human exposure Specific Absorption Rate (SAR) values in 5G with adaptive MaMIMO antennas.
- A multi-objective optimisation algorithm reducing the overall SAR for the UL and DL values (jointly or separately), while maintaining the quality requirements of the network service.
- A Mixed-Integer Programming (MIP) network solver to achieve optimal network coverage and capacity under human exposure limits, for various technologies and frequencies.
- A coverage and capacity analysis for a realistic 3D environment considering future 5G traffic and detailed penetration parameters of the building for multi-operator, multi-technology and multiple mobile networks.

This paper is organised as follows. Section 2 presents the related work on 5G MaMIMO network planners and its relationship with human exposure. Section 3 reviews wireless technologies and defines performance and exposure metrics. In Section 4, the evaluation framework used in the study is presented. Section 5 describes the simulation algorithm and the multi-objective optimisation methods. The simulated results are discussed in Section 6 while Section 7 concludes the paper.

2. 5G massive MIMO network planning with respect to exposure

Based on the requirements of diverse government bodies, there is a need of network planners that account for all the aspects of the 5G networks, in particular the ones that include exposure analysis in their solutions. There are several commercial network planners that could investigate the performance of 5G networks [4–8], but none of them account for exposure restrictions. Now that 5G networks are becoming a reality which includes new characteristic such as MaMIMO and its directive beams, researchers and software providers are required to put special attention to the electromagnetic field calculations, in order to plan networks that do not exceed the limits found in recommendations [3]. Some of these tools, that account for human exposure, are presented in the following two groups: (i) the statistical/theoretical models and (ii) the deterministic/realistic models. Table 1 summarises these works.

2.1. Statistical models

In the literature, there is a vast number of references that explore statistical models for human exposure in mobile networks. Marzetta et al. [1] provide diverse case studies for multicell MaMIMO deployments for hexagonal cells in various environments, showing that the number of deployed BSs depends on the transmitted power per beam and the requested traffic per user. In [9], a 3D statistical model is created to determine the safety distances in MaMIMO, showing that these distances are almost half in 5G compared to 4G sectorised antennas while reducing the transmitted power to 30%. Similarly, in [10], the modelling of a realistic MaMIMO antennas determines that safety distance are reduced from 25 m (pre-5G networks) down to 16.5 m in 5G MaMIMO networks. The paper in [11], shows that the time-averaged transmitted power varies between 7% and 22% of the maximum transmitted power if a statistical approach of user requirements within a cell is used. The pencil-beams 5G network planner on [12] demonstrates that the overall electromagnetic exposure (EMF) is reduced if the users' location uncertainty is reduced (from 20 m down to 2 m) leading to increments in the users' throughput. In [13], a stochastic method is used to determine the E-Field in an indoor scenario, obtaining similar results using only 10% of computational efforts of the deterministic tool in [14].

2.2. Deterministic models

Plets et al. [14,15] introduced a heuristic tool for exposure in indoor environments that uses a method to reduce exposure of indoor users. Matalatala et al. [16] introduce a multiobjective optimisation algorithm to deploy cost-effective 5G networks that are aware of the exposure to electromagnetic UL and DL while providing maximum user coverage. Results show that the increment of the number of 5G BS due the increased traffic tend to reduce the DL exposure by 12% while the UL exposure is increased by 70%. [17] introduced a Ray tracking (RT) method into the 5G network planner, in order to obtain detailed knowledge of the propagation environment. The exposure values reported show that the localised DL_{10g} and the DL_{wba} from a BS with 64 antenna elements is 31% higher and 46% lower respectively, compared with a BS with 16 antenna elements. The work in [18] compares the performance of an RT method with a Rayleigh fading channel model for a large scale MaMIMO network with different antenna configuration, showing that only large linear arrays produce comparative results. Chiaraviglio [19] proposes a Mixed-Integer Programming (MIP) heuristic optimisation model to determine the optimal coverage under the installation cost of a 5G deployment, showing that the results are highly sensitive to the maximum exposure limits and the amount of pre-5G technologies.

2.3. 5G exposure measurements

The in-situ measurement methodology presented in [20] determines that the actual maximum exposure level could be determined with a reduced exposure measured time if detailed network configuration parameters are known. Further measurements of a commercial 5G base station found that the average exposure is 9.5% of the total RF exposure when the maximum DL traffic is forced [21]. Similarly, the work in [22] found that maximum instantaneous exposure is 0.23% of references levels in the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [23]. The measurements done by Ericsson using a 4G [24], and a 5G [25] commercial MaMIMO networks demonstrate that the actual transmitted power per beam is well below the theoretical maximum and lower than predicted statistical models, that is, 14% of the maximum theoretical in 4G and 25% of the maximum theoretical in 5G, leading to safety distances 5 times smaller. The work in [26] compares the simulated values with the measured EMF values to evaluate the spherical formula of the far field, obtaining similar results if the traffic beam patterns are known. [27] presents a multibeam multi-user 5G test-bed where the exposure values measured are far lower than the exposure limits.

3. Wireless networks and performance metrics

This section describes the methodology used to analyse mobile network topologies and their effect on human exposure, network quality, and sustainability in Switzerland.

Table 1
Work positioning with respect to the other relevant papers in the literature.

Work	Model	Main investigation	Scenario	Contributions and Findings
[9]	3D Statistical modelling	Time averaging exposure for spatial channel models in Massive MIMO networks.	Urban Macro/Micro Outdoor or Indoor	Reduction of compliance distances down to 1/2 for MasssiveMIMO networks.
[10]	Received power by distance calculations.	Exclusion Zones for 5G active antennas	Urban/Suburban/Rural Outdoor only	5G replacement of legacy network decreases safety distances from 25 m down to 16 m.
[11]	Time- averaged Statistical modelling	BS utilisation, TDD scheduling and spatial distribution impact on the Efield.	Urban/Rural Outdoor only	The statistical modelling shows a reduction of 7%–22% of the maximum theoretical EFM.
[12]	5G's pencil beamforming with localisation-enhanced	Pencil Beamforming impact on the EMF over cellular coverage area	Urban Micro Street Canyon Outdoor Only	The EMF is reduced if the uncertainty of the users is reduced and thus the throughput will increase.
[13]	2D model combining PCA and Kriging method.	Determination of the indoor exposure map.	Residential Indoor Only	Simulation time is reduced to 10% of the WHIPP tool.
[14,15]	2D indoor heuristic tool	Optimised location of Indoor Access Points to reduce exposure.	Residential Indoor Only	Wifi network optimised to not exceed Efield limit and increase its homogeneity while reducing exposure 60%.
[16]	5G deterministic network planning with exposure optimisation.	Capacity and network performance, electric field and exposure dose.	Suburban Outdoor only	The increment of BS antenna elements contributed to 12% DL exposure reduction while UL rises by 70%
[17]	5G Ray tracing and Finite Difference Time Domain (FDTD)	Increased accuracy in the eField calculations for UL and DL exposure. (Whole body and 10 g localised)	Suburban Outdoor only	Optimise MassiveMIMO network planning under power and exposure constraints. Accounting for detailed exposure values.
[18]	Ray tracing large scale deterministic model.	Evaluation of diverse MassiveMIMO arrays and comparison of deterministic path loss models.	Urban Outdoor only	Simulation demonstration of practical Massive MIMO systems with diverse real propagation conditions.
[19]	Heuristic MIP optimisation model	Maximisation of Throughput, coverage distance and required SINR.	Urban Outdoor only	The optimisation method shows that network size is dependent on exposure limits and legacy technologies.
This work	3D simple RT with network optimiser planner	Realistic 4G and 5G network performance and UL and DL Exposure Ratio parameters.	Urban/Suburban/Rural Outdoor and Indoor	Exposure is dominated by UL (10X than DL). 5G DL exposure is 4/3 the one from 4G, while 5G UL exposure is 3/4 the one in 4G.

3.1. Wireless technologies

3.1.1. 4G — long term evolution

For 4G, Long Term Evolution-Advanced (LTE-A) was considered as the underlying 4G technology in this study. LTE-A comprises a group of features that are adopted from the 3GPP Release 10 [28,29] or later and provides the following upgrades compared to the previous LTE standards: (i) Increase of the data bit rate, (ii) Larger flexibility of the spectrum allocation, (iii) Latency reduction and (iv) Better communication efficiency. One of the key features of LTE-A is the use of carrier aggregate (CA). It aims to maximise the bandwidth of an operator from 20 MHz up to 100 MHz, by using different carriers, achieving user bit rates of up to 1 Gbps. For this study, an LTE-A network with a carrier aggregation of up to five carriers was considered at 800 MHz and 2100 MHz, which are two frequency bands that are commonly used for 4G cellular communication. An overview of all the 4G network parameters can be found in Table 2. Table 3 shows the receiver sensitivity for the various combinations of modulation and coding schemes (MCS).

3.1.2. 5G — New radio

5G NR is currently considered the novel standard for next-generation networks. 5G introduces a paradigm shift towards a user and application-centric technology framework, supporting three important use cases: (i) Enhanced Mobile Broadband (eMBB), (ii) Machine Type Communications (mMTC) and (iii) Ultra-reliable Low Latency Communications (ULLC) [30]. For this study, we focus on the first application domain, that is, eMBB. 5G NR Release 14 enables the use of an advanced antenna array system including up to hundreds of antenna elements, which are called MaMIMO, to drastically increase the obtained throughput [31]. MaMIMO bundles all data and signalling towards the user, which positively influences the link budget and reduces interference, resulting in higher data rates. This is a different approach compared to 4G, where the BS cell typically consists of three sectors, each covering 120 degrees. The disadvantage of using such a 'broad' bundle is that if one wants to send the signal to a single user, the signal must be sent to the entire sector, which negatively impacts the link budget and causes interference. For our simulations, we assumed that 50% of the BSs in a 5G network will use MaMIMO technology at a frequency of 3500 MHz. All other BSs in the network will support only 5G NR and replace the current existing 4G technology on the 800 MHz and 2100 MHz frequency bands. Tables 2 and 4 show the network parameters and receiver sensitivities for the 5G NR technology, respectively. Based on Table 4 it becomes obvious that for 5G networks with bandwidth <80 MHz, the maximum supported bit rate will be less than 1 Gbps.

3.1.3. Frequency ranges

In Switzerland, various frequency ranges and bands are available for 4G and 5G mobile communications and are shared between operators.

In order to reduce the demands on the simulation size, we grouped frequency ranges with similar propagation and absorption characteristics while maintaining the available bandwidth per operator in each frequency group. As a result, we defined three carrier frequencies at 800 MHz, 2100 MHz for 4G and 5G, and 3500 MHz for 5G only.

Based on these maximum available bandwidths, we assigned upper bandwidth bounds for the different operators and mobile communication systems, as shown in Table 5.

Table 2
Network parameters used for the simulation of 4G LTE-A and 5G NR mobile networks (see Tables 3 and 4).

	Parameter	Unit	4G 800	4G 2100	5G 800	5G 2100	5G 3500
Band	Simulated frequency	MHz	800	2100	800	2100	3500
	Channel bandwidth (max available)	MHz	100	100	120	120	120
	Used subcarriers	#	6010	6010	7680	7680	7680
	Total subcarriers	#	10240	10240	12288	12288	12288
	Sampling factor	–	1536	1536	1536	1536	1536
	TDD duty cycle dl	%	N/A	N/A	75	75	75
	TDD duty cycle ul	%	N/A	N/A	25	25	25
	Spatial duty cycle	%	N/A	N/A	0	0	15
TX/RX	BS transmit antenna gain (total)	dBi	17	18	16	18	24
	BS transmit array antenna feed loss	dBi	2	2	2	2	3
	BS total radiated power (new sites)	dBm	43	49	46	49	53
	BS number of antenna elements	#	1	1	1	1	64
	MS receive antenna element gain	dBi	0	0	0	0	0
	MS transmit power	dBm	23	23	23	23	23
	MS antenna height	m	1.5	1.5	1.5	1.5	1.5
	MS number of antenna elements	#	1	1	1	1	1
	Rx noise figure	dB	8	8	8	8	7
Propagation	Path loss model	–	TR 38.901	TR 38.901	TR 38.901	TR 38.901	TR 38.901
	Low building loss (70%)	dB	12.4	12.6	12.4	12.6	12.9
	High building loss (30%)	dB	29.8	30.2	29.8	30.2	30.6
	Other losses (shadow, fading)	dB	22.8	25.2	22.8	25.2	20
	Safety distance (user-bs)	m	15	15	15	15	15
SNR	SNR required for 100 Mbps	dB	10.5	10.5	0 @120 MHz	0 @120 MHz	0 @120 MHz
	SNR required for 1 Gbps	dB	N/A	N/A	27 @120 MHz	27 @120 MHz	27 @120 MHz

Table 3
SNR values and corresponding Bit-rates for 4G LTE-A.

Modulation	CR	SNR [dB] BLER = 10%	Bandwidth [MHz]			
			Bitrate [Mbps]			
			50	60	80	100
BPSK	1/10	−2.0	5.0	6.0	8.0	10.0
BPSK	1/8	0.0	6.3	7.5	10.0	12.5
BPSK	1/6	1.0	8.3	10.0	13.3	16.7
QPSK	1/1	2.0	10.0	12.0	16.0	20.0
QPSK	1/2	10.5	50.0	60.0	80.0	100.0
16QAM	1/3	14.0	62.5	75.0	100.0	125
16QAM	5/12	17.0	83.3	100.0	133.3	166.7
16QAM	1/2	21.0	100.0	120.0	160.0	200.0
16QAM	3/4	29.4	216.0	256.0	348.0	438.0

3.2. Human exposure metrics

Human exposure is addressed by the study of the total exposure of the network, which can be considered as the sum of UL and DL exposure compared to their safety limits. These ratios are known as the exposure ratios, described in Section 3.2.1, and can be reported separately. Although the dominant source of the human exposure is the UL exposure as previously described in [32,33], in mobile communication system the total exposure metric is applied. The following subsection describes the exposure limits as well as the dosimetric quantities used in this study.

3.2.1. Exposure ratios

To combine the DL and UL exposure, the exposure ratio (ER) is defined. ER is defined as the ratio of the measured SAR value over the SAR limit normalised with the exposure time. In particular, the ER_{DL} is the DL SAR at any time normalised with the whole-body average (wba) SAR limit as in Eq. (1), while the ER_{UL} is the UL SAR normalised by the 10 g SAR limit shown in Eq. (2).

$$ER_{DL} = \frac{1}{T_{REF}} \cdot \frac{SAR_{DL_{wba}}}{SAR_{lim_{wba}}} \cdot T_{DL} \tag{1}$$

$$ER_{UL} = \frac{1}{T_{REF}} \cdot \frac{SAR_{UL_{10g}}}{SAR_{lim_{10g}}} \cdot T_{UL} \tag{2}$$

T_{REF} has been defined based on the averaging time of 6 min specified for the basics restrictions for local SAR according to the ICNIRP guidelines [3]. The T_{DL} and T_{UL} reflect the exposure duration compared to the reference interval (T_{REF}) for the downlink and the uplink. For T_{DL}, a constant exposure over the 6 min is assumed. In particular, human exposure should be considered as an average of 6 min, as defined by [23]. The time-averaging method implicitly includes the effect of the correction factors defined in [34]. The use of time-averaging on how exposure is limited in modern mobile devices that use the Time-Averaged SAR (TAS). This allows control of the mobile device's output power to ensure compliance with the specific SAR limit when time averaged over 6 min [35]. On the other hand, for the UL, the exposure duration in the reference interval is $T_{UL} = 3.5$ s, based on literature data [16]. We assume a homogeneous exposure of the whole body from the DL signal and a localised exposure from the UL signal of a user's own mobile device.

Normalising the DL SAR and UL SAR to the specific safety limits allows the two contributions to be added up in terms of total exposure ratio ER_{total}, which is the sum of independent ER_{DL} and ER_{UL} as described in Eq. (3).

$$ER_{total} = ER_{DL} + ER_{UL} \tag{3}$$

The limits used for the calculation of the ER are defined by ICNIRP [23]. For the DL direction, the limit for the wba SAR is defined by $SAR_{lim_{wba}} \leq 0.08$ W/kg, while for the UL direction, the limit for the localised SAR over $10g$ of tissue is defined by $SAR_{lim_{10g}} \leq 2$ W/kg. The definition of the $SAR_{DL_{wba}}$ and $SAR_{UL_{10g}}$ are described in Sections 3.2.2 and 3.2.3 respectively.

3.2.2. Downlink induced SAR

The DL SAR ($SAR_{DL_{wba}}$) from the network at any location is calculated based on the sum of the incident power densities (S_{BS_j}) for all j BSs multiplied with the DL SAR conversion factor ($SAR^{REF}_{DL_{wba}}$) in Table 6.

$$SAR_{DL_{wba}} = SAR^{REF}_{DL_{wba}} \cdot \sum_{j=0}^{n} S_{BS_j} \tag{4}$$

The DL SAR conversion factors were calculated based on numerical simulations [17] and are summarised in Table 6.

Table 4
SNR values and corresponding Bit-rates for 5G NR.

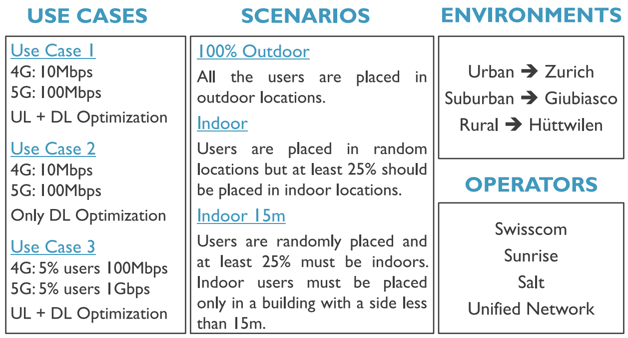
MCS Index	CQI	Modulation	CR × M Order	SNR [dB] BLER = 10%	Bandwidth [MHz] Bitrate [Mbps]				
					50	60	80	100	120
1	2	QPSK	0.38	−3.0	44	52	70	86	98
3	3	QPSK	0.88	0.0	56	50	96	100	100
5	4	16QAM	1.48	3.0	86	100	100	170	208
7	5	16QAM	1.91	5.0	100	144	188	236	288
21	12	256QAM	5.55	27.0	416	488	664	832	1000
23	13	256QAN	6.23	29.0	486	592	774	1000	1184
27	15	256QAM	7.41	30.0	*614*	*722*	1000	1230	1498

Table 5
Bandwidths upper bound per simulated carrier frequency and operator for 4G and 5G communication systems.

Frequency		800 MHz		2100 MHz		3500 MHz
Technology	Units	4G	5G	4G	5G	5G
Operator 1	MHz	80	80	100	120	120
Operator 2	MHz	60	60	100	120	100
Operator 3	MHz	50	50	100	120	80
Unified	MHz	100	120	100	120	120

Table 6
DL SAR and UL SAR factors to convert the incident power density into whole-body averaged SAR and 10 g averaged SAR, respectively. Values from Refs. [17,36,37].

Frequency/MHz	$\mathrm{SAR}^{\mathrm{REF}}_{\mathrm{DL}_{\mathrm{wba}}} / \frac{\mathrm{mW/kg}}{\mathrm{W/m^2}}$	$\mathrm{SAR}^{\mathrm{REF}}_{\mathrm{UL}_{10g}} / \frac{\mathrm{W/kg}}{\mathrm{W}}$
800	6.96	0.55
2100	5.84	2.15
3500	4.8	2.26



All the users are placed in outdoor locations.

Users are placed in random locations but at least 25% should be placed in indoor locations.

Users are randomly placed and at least 25% must be indoors. Indoor users must be placed only in a building with a side less than 15m.

Fig. 1. Overview of the scenarios applied to optimise mobile communication networks for low human exposure, communication quality, and sustainability.

3.2.3. *Uplink induced SAR*

The UL SAR conversion factors ($SAR^{REF}_{UL_{10g}}$) shown in Table 6 are used together with the mobile device transmit duty cycle (DC^{UL}_{TDD}) and its output power (P_n) to determine the SAR ($SAR_{UL_{10g}}$) of the mobile device:

$$SAR_{UL_{10g}} = SAR^{REF}_{UL_{10g}} \cdot P_n \cdot DC^{UL}_{TDD} \tag{5}$$

$$P_n = 10^{\frac{min(RX_{sens}+PL,23)}{10}} \tag{6}$$

$$RX_{sens} = 10 \cdot log_{10}(KTB) + NF + SNR. \tag{7}$$

The power output of the mobile device is limited to 23 dBm, and the power control is implemented dependent on the PL and the receiver sensitivity RX_{sens} (in dB). RX_{sens} is calculated as a function of the thermal noise floor KTB, system noise figure NF, and the required Modulation and Coding Scheme (MCS) which is dependant of the Signal to Noise Ratio (SNR). $SAR^{REF}_{UL_{10g}}$ have been determined by frequency band-specific averaging of measured SAR values of two modern mobile devices over all standardised SAR test positions [36,37].

3.2.4. *Incident E-field limit*

Limits of the incident electric fields E_{tot} were defined based on [38]. Here, a BS site limit of 5 V/m was established defined as $E_{tot} = \sum_{f=800}^{3500} E_f \leq 5$ V/m, where E_f is the electric field per technology frequency used. All simulated indoor and outdoor locations have to satisfy this limit. A protection zone of 15 m around all BSs is assumed, where no mobile users were placed [10]. This implies that within the protection zone, levels greater than 5, V/m may occur.

3.3. *Network performance*

Network quality is addressed by introducing network performance criteria reflecting the traffic requirements of 4G and 5G networks extrapolated to the year 2030 in Switzerland. These data were collected from one of the Swiss mobile operators and extrapolated based on their growth rate and market share [39–41]. It was tested that the networks can be implemented by ensuring that performance is met with a user coverage of at least 95% (see Table 6.1 in [1]) in the three regions, described in Section 4.2.

Sustainability is addressed by (i) projecting data usage and user requirements to the year 2030 in our evaluations, (ii) weighting network power consumption (iii) assessing the number of required BSs in separate and unified networks, and (iv) analysing the suitability of 4G and 5G networks to serve the data communication requirements of the future.

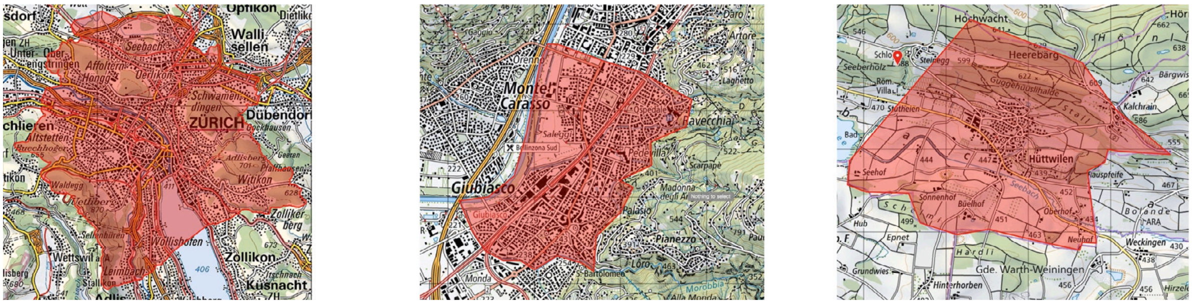
4. Evaluation framework

The following section describes the considered scenarios used in our simulations. First, we present the Use Cases, where traffic requirements and planning optimisation methods are described. Second, the urban, suburban and rural Environments and the Switzerland cities that represent them are shown. Next, we focus on the users' location describing the Coverage Scenarios for indoor or outdoor placement. Then, the different Network operators are described. Finally, the users and traffic for the year 2030 are presented. All of them are summarised in Fig. 1.

4.1. *Use cases*

The Use Cases are defined to investigate the impact of the network optimisation towards the DL and UL human exposure. Also, they attain the impact of the high bitrate requirements for users. In Use Case 1 (UC1), the requirements for a 4G network entail a guaranteed data rate of 10 Mbps for all users, while the guaranteed data rate was set to 100 Mbps to represent the demands on a 5G network. In this use case, the exposure minimisation in UL and DL were weighted equally, 40% each, while energy consumption is set to 20%.

For Use Case 2 (UC2), the same data rates as for UC1 were assumed, but the network was optimised for low exposure in the DL only. A network with the same quality of service as for UC1 can be analysed, but it aims to minimise the exposure of non-users. In this use case,



(a) Zurich

(b) Giubiasco

(c) Hüttwilen

Fig. 2. Maps of the three simulated regions (a) Zurich: urban, (b) Giubiasco: suburban, (c) Hüttwilen: rural.

Table 7
Environment region and its areas.

Environment	Region	Size km^2	Density pp/km^2
Urban	Zurich	70.4	5897
Suburban	Giubiasco	3.7	2216
Rural	Hüttwilen	5.9	288

Table 8
Number of available sites per environment and operator.

Operator	Zurich	Giubiasco	Hüttwilen
Operator 1	815	23	7
Operator 2	859	29	4
Operator 3	260	24	1
Unified	1898	64	12

DL exposure minimisation was weighted with 80%, while the network energy consumption is maintained in 20%.

In Use Case 3 (UC3), the network was optimised to serve the peak data requirement for the future of 4G and 5G networks, i.e., 100 Mbps and 1 Gbps, for 5% of the users, while the other users has 10 Mbps and 100 Mbps respectively.

4.2. Environment

In order to account for diverse population densities, we consider three study regions covering urban (Zurich), suburban (Giubiasco) and rural (Hüttwilen) environments in Switzerland. The characteristics of these regions are presented in Table 7 and the maps are shown in Fig. 2. To account for the characteristics of the environment in the network planner, 3D building models were acquired and used in the simulation model [42].

The propagation model used for these environments is from the 3GPP TR 38.901 specification [43] which considers urban (UMa) and rural (RMa) environments. As there was no dedicated model defined for a suburban environment, we applied the UMa model for this one. Furthermore, for the penetration loss of the buildings, we separated a low and a high building loss obtained from the ECC report 302 and ITU-R P.2109 recommendation [44,45]. In our simulations, there is a 70% chance of having a low building loss and a 30% chance of having a high building loss, as shown in Table 2. The path loss (PL) PL_u for a user could be described as follows:

$$PL_u = PL_{outdoor} + B_{Loss} \tag{8}$$

Where B_{Loss} is the loss value of the building described as 0 dB for outdoor users or the values described in Table 2 for indoor users. The $PL_{outdoor}$ is the PL value in dB defined in table 7.4.1-1 for the Line-of-Sight (LoS) or Non-Line-of-Sight for UMa and RMa scenarios in 3GPP TR 38.901 [43].

4.3. Coverage scenarios

The coverage scenarios define the location of the users on the investigates area. These are defined to investigate the impact of outdoor and indoor users into the exposure evaluation. We defined three scenarios to investigate only outdoor users, outdoor and indoor users and indoor users in small houses.

Scenario Outdoor: All mobile network users were randomly placed in outdoor locations. This scenario is used to plan a mobile communication network that is optimised to provide sufficient coverage only for outdoor locations. Indoor wireless coverage would need to be provided by other means, e.g., separate Wi-Fi or 4G/5G femtocells, and is not included in the scope of this study.

Scenario Indoor: In this scenario, the network was optimised to provide full outdoor and indoor coverage from outdoor BSs. 25% of the users are randomly distributed within buildings in the simulations. The rest (75%) of the users are randomly placed in outdoor locations.

Scenario Indoor 15 m: This scenario is similar to the previous one, with the difference that the mobile network is optimised for outdoor coverage and coverage of small buildings only, with a maximum side length (or street side) of <15 m.

4.4. Network operators

The network operators for the study were considered as they are currently positioned in Switzerland in terms of available BS locations and market shares [40,46]. This was needed to determine the amount of users and the number of available BS for each simulation. Additional to the existing operator networks, we also considered a “Unified network”, which considers that all the BS locations currently available to any operator are available in the network planning. The Unified network is also designed to serve the sum of the users and data usage of all current operators.

The BS location and configuration data for the three study regions were provided by the Swiss Federal Office of Communications (OFCOM) active in Switzerland. In this paper we refer to these locations as sites, and depending on the communication technology at each site can serve multiples frequencies.

In case the user coverage requirement of 95% could not be met, an extended BS list was used. This extended list is created by adding additional sites within a random distance (between 100 m and 1 km) of existing sites in order to maintain similar BS distribution among the investigated area, following the operators’ recommendations of previous network extensions. After an iteration for all the sites was concluded, the new extended list was evaluated. Typically, between three to seven iterations are required until the user coverage surpasses the 95% limit for the specific network. The number of BSs used in the simulation is provided in Table 8.

Table 9
Projected number of users for each environment.

Operator	Zurich	Giubiasco	Hüttwilen
Operator 1	5546	369	139
Operator 2	2466	164	62
Operator 3	1583	105	40
Unified	9595	638	241

4.5. *User density and traffic*

For all the described scenarios, environments and use cases, the user traffic usage data was collected from measurements by the active mobile operators in Zurich, Giubiasco, and Hüttwilen between October and November 2020 (31 days). The data shows that the peak hour is between 3 pm and 4 pm. For this timestamp, 1984, 132 and 50 users (aggregated over the three networks) were simultaneously active for respectively Zurich, Giubiasco and Hüttwilen. To estimate the number of users in 2030, the compound annual growth rate (CARG) of 2.2% is considered, which is based on the adoption of the mobile internet and smartphones in Switzerland [39,40]. To determine the number of users for each operator, the Swiss market distribution (dated December 2020) was considered: 56.7% for operator 1, 23.9% for operator 2, 15.3% for operator 3, and 4.1% for others [46]. Table 9 shows the number of simultaneous active users for each operator and environment.

5. Network planning and optimisation

5.1. *Simulation tool*

The network planner used for this study is the GRAND (Green Radio Access Network Design) deployment tool developed by the WAVES research group at Ghent University [47]. This tool designs wireless outdoor access networks optimised for power consumption and/or human exposure, based on the number of active users and their instantaneous bit rate request in 3D environments.

5.1.1. *Input*

As the tool is capacity-based, it is important to have a realistic view of the number of users, their bit rate requirements, location, and environment. Therefore, the tool considers the following input:

- *Input 1 — Shape-file of the environment:* Contains detailed 3D information about the buildings (i.e., location, shape, height, etc.) in the selected environment and the tool uses this to determine if a user is in LoS or NLoS of a certain base station and if it is indoors or outdoors.
- *Input 2 — Max number of users:* The maximum number of simultaneous users that is active in the area considered. This is confidential data provided by mobile operators.
- *Input 3 — Location distribution:* Determines the location of the active users in the area; in this case an uniform distribution is used.
- *Input 4 — Bit rate distribution:* Defines the bitrate demanded by each user.

In addition to information about the environment and user traffic, the link budget parameters for the considered wireless technology and a list of possible BS locations in the environment are also provided to the tool.

5.1.2. *Mixed-integer programming solving algorithm*

The core of the GRAND tool is the heuristic algorithm that optimises user coverage, the network's power consumption, and/or human exposure, under certain constrains. Regarding human exposure, two optimisation strategies are possible: (i) UL and DL optimisation which is a network optimised for both users and non-user exposure, and (ii) DL only optimisation which is optimised for non-users as described previously. The first is used to evaluate UC 1 and UC 3 of our evaluation strategy, while the second investigates UC 2 (see Section 4.1)

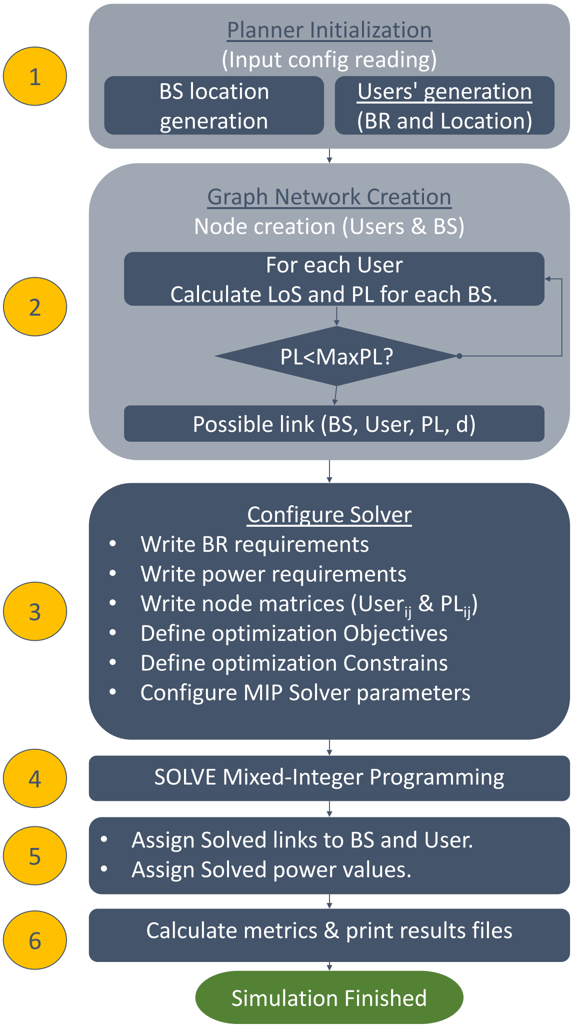


Fig. 3. Solver algorithm for the GRAND tool.

The optimisation algorithms is shown in Fig. 3. First in *Step 1*, the simulation is initialised, by reading all the input and configuration parameters for the simulation. When all input data has been read, the tool determines the location and bitrate requirements of each user. In *Step 2*, the tool initialises a *graph* with all users and BSs (known as nodes in the *graph*); and calculates the PL values between them. A possible link (known as the edge in the *graph*) is created if the PL between the evaluated user and the BS is under the maximum supported SNR of the PL for the required bit rate. Once all the users are evaluated, the *graph* is completed and ready to be evaluated for the Mixed-Integer Programming (MIP) solver. In *Step 3*, the tool assigns constraints to the *graph* and MIP solver by defining optimisation objectives based on bitrate requirements and power restrictions and configures them among the solver parameters [48]. (See Section 5.2.) In *Step 4*, the MIP solver investigates the most optimal solution(s) and selects the one with the highest objective values. Based on the optimal solution, the algorithm assigns users to the selected BS and calculates the performance metrics in *Step 5*. Finally, in *Step 6*, the tool logs the results in output files for further post-processing.

5.1.3. *Output*

As output, the GRAND tool provides various quantitative results such as the number of used BSs, the network's offered capacity, the

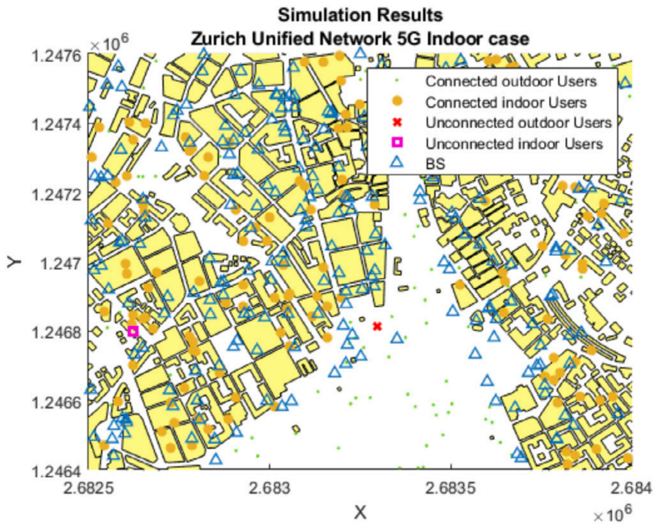


Fig. 4. Use Case 1 intermediate result snapshot in Zurich city center.

number of covered users, the area coverage, the network's global exposure, the electric field, the SAR and the ER for all users (both for DL and UL) [47]. An example of the output files with the shape buildings and connected/unconnected locations is presented in the results section in Fig. 4.

5.2. Multi-objective optimisation methods

The network planning optimal solution was achieved by using a multi-objective solver. We aim to fulfil four objective problems: (i) Maximise user coverage, (ii) Minimise average path loss, (iii) Minimise averaged DL exposure, and (iv) Minimise averaged UL exposure. In Eq. (9), the multi-objective fitness function is described.

$$O = \frac{-w_0 * UC_{fitness}}{U} + \frac{w_1 * PL_{fitness}}{PL_{worse}} + \frac{w_2 * DL_{fitness}}{DL_{worse}} + \frac{w_3 * UL_{fitness}}{UL_{worse}} \tag{9}$$

Where w_0 to w_3 are the weights respectively for the user coverage, PL, DL exposure and UL exposure functions. $\frac{UC_{fitness}}{U}$ is the normalised user coverage function, $\frac{PL_{fitness}}{PL_{worse}}$, $\frac{DL_{fitness}}{DL_{worse}}$ and $\frac{UL_{fitness}}{UL_{worse}}$ correspond to the normalised fitness functions, for the PL, DL exposure and UL exposure.

User coverage function:

The user coverage fitness function ensures that the coverage requirement in the system is met, and is defined as follows:

$$UC_{fitness} = \max_{\{i,j\}} \left(\sum_{i=1,j=1}^{\substack{i=U \\ j=BS}} X_{ij} \right) \tag{10}$$

Where i is the index of the evaluated user and j is the index of the evaluated BS. U is the number of total users and BS is the total number of BS available. X_{ij} is the binary variable that determines whether user i is assigned to BS j. This is subject to $\forall i \in \mathbb{N}$, $\forall j \in \mathbb{N}$ and $X_{ij} \in \{0, 1\}$.

Path loss function:

The PL fitness function aims to choose the link with the minimal propagation loss. This will lead to smaller SNR values that will result in higher supported bit rates. It is determined by the following Equation:

$$PL_{fitness} = \min_{\{i,j\}} \left(\sum_{i=1,j=1}^{\substack{i=U \\ j=BS}} PL_{ij} * X_{ij} \right) \tag{11}$$

Table 10
User coverage obtained by the original BS set (Org) or with the extended BS set (Ext) (Underline = user coverage goal of 95% is met; *Italic* = user coverage goal is not met).

Operator	BS Set	Zurich		Giubiasco		Hüttwilen	
		4G	5G	4G	5G	4G	5G
Operator 1	Org	*94.5%*	*94.6%*	*94.5%*	*93.4%*	*58.9%*	*65.3%*
	Ext	98.0%	98.1%	98.1%	98.1%	97.6%	97.7%
Operator 2	Org	97.6%	97.1%	*82.7%*	*87.5%*	*52.2%*	*50.7%*
	Ext	–	–	98.2%	98.2%	97.4%	95.9%
Operator 3	Org	96.2%	95.8%	*81.8%*	*80.4%*	*26.3%*	*26.6%*
	Ext	–	–	98.1%	98.1%	99.8%	99.9%
Unified	Org	98.0%	96.5%	98.1%	98.1%	*66.8%*	*68.1%*
	Ext	–	–	–	–	97.3%	97.1%

Where PL_{ij} is the propagation loss between user i and BS j, as defined in Eq. (8) in Section 4.2 and table 7.4.1-1 of [43].

DL exposure function:

The DL exposure fitness function focusses on reducing the overall transmitted power of the BS by accounting for the exposure limits.

$$DL_{fitness} = \min_{\{i,j\}} \left(\sum_{i=1,j=1}^{\substack{i=U \\ j=BS}} SAR_{DL_{wba_{ij}}} * BS_{Active_j} \right) \tag{12}$$

Where $SAR_{DL_{wba_{ij}}}$ is the whole body DL SAR value calculated in user i from BS j as defined in Eq. (4), multiplied by the binary variable BS_{Active_j} that determine if BS j is active.

UL exposure function:

The UL exposure accounts for the owner's mobile equipment and the nearby other users' equipment. It is defined as follows.

$$UL_{fitness} = \min_{\{i\}} \left(\sum_{i=1}^{i=U} SAR_{UL_{10g_i}} * X_i \right) \tag{13}$$

Where $SAR_{UL_{10g_i}}$ is the 10 g UL SAR value described in Eq. (5) for the user i. X_i is the binary variable that determines whether or not the user i is active.

6. Simulation results

Sections 6.1–6.6 summarise the main results of the study.

6.1. Network coverage and base station requirements

The user coverage achieved for UC 1 is presented in Table 10. For some of these networks and environments (indicated in italics), the user coverage obtained with the original BS set was below the envisioned target of 95%. For these operator-environment configurations, the set of BSs was further extended until a user coverage of at least 95% was obtained, as described in Section 4.4. Results show that in the rural and suburban scenarios, all the operator configurations need the extended list due to the low density of active BS in these areas. However, it should be noted that in our study, no sparsely populated areas had to be covered. For the urban environment, operator 1 needed the extended list since it has the highest ratio between users and available BSs, which leads to a higher demand for BS, in particular for 5G massive MIMO network. In particular, the extended list is needed to support the future 5G user requirements for the year 2030.

Table 11 shows the number of BSs used by the various networks and usage scenarios to obtain 95% user coverage. In general (for both the unified and the operator networks), to obtain the same level of user coverage, the 5G network will use on average about three times as many BSs as the 4G network, due the fact that 5G requires 10 times more capacity. For UC 1 and the outdoor scenario (Table 11a), the 5G network requires a factor of 3.35 more sites in the city of

Table 11
Number of Base stations needed in different simulations.

Operator	Zurich		Giubiasco		Hüttwilen	
	4G	5G	4G	5G	4G	5G
Operator 1	167	521	16	32	5	13
Operator 2	67	214	6	16	3	6
Operator 3	38	120	8	18	2	4
Unified	161	595	15	49	7	20

(**a**) Use case 1 Outdoor-only scenario.

Scenario	Zurich		Giubiasco		Hüttwilen	
	4G	5G	4G	5G	4G	5G
Outdoor	161	595	15	49	7	20
Indoor	258	680	18	52	7	21
Indoor 15 m	268	684	18	52	7	20

(**b**) Use case 1 for Unified network.

Scenario	Zurich		Giubiasco		Hüttwilen	
	4G	5G	4G	5G	4G	5G
Outdoor	201	702	12	45	8	21
Indoor	207	802	18	52	8	21
Indoor 15 m	230	751	18	52	8	21

(**c**) Use case 3 for Unified network.

Zurich compared to a factor of 2.5 in Giubiasco and Hüttwilen. The 5G network in the urban environment (i.e., Zurich), requires more sites to compensate for the higher number of NLoS situations compared to the other environments, due taller and denser buildings. To deliver such a high data rate, the network has to be denser. In addition, the 5G MaMIMO BSs can only support a limited number of eight users.

Unifying the network has a positive influence on the number of BSs present in all environments. For all environments, the sum of the number of BSs required for individual operators is greater than the number of BSs required by the unified network. For 4G, 41%, 50%, and 30% fewer BSs are required for the unified network compared to the sum of the separate networks for the urban, suburban, and rural scenarios, respectively. For 5G, reductions of 30%, 26%, and 13% were found. This is due to the increased number of BSs available per area in the unified network, leading to more connected users per BS in the unified network. Including the indoor users into the coverage solution (Table 11b), the number of required BSs increases for the 4G networks in environments with high building density (urban: +60%, suburban: +20%, rural: +0%), due to the increase in the PL that reduces the available BS capacity. In 5G networks, the requirement for additional BSs is much lower (urban: +14%, suburban: +6%, rural: +5%). In 5G, the BS density is driven by high data rate requirements such that additional building losses have little impact on the networks.

Table 11c lists the BS requirements for UC 3. In the urban environment, a higher number of BSs is required for UC 3 compared to UC 1. Overall, the relative increase in the number of additional BSs to support the high data rate is small. There are cases with a lower BS count in the UC 3 compared with the UC 1 (urban, indoor and suburban Indoor, and Indoor 15 m). The reason for this is that we allow user coverage between 95% and 100%, implying that a small change in user coverage could lead to significant changes in BS count. Here, in UC 3, the user coverage drops by 1% on average compared to UC 1, resulting in a lower BS count.

6.2. Exposure in outdoor scenarios

Fig. 5 shows the statistical summary values (p_{50}, p_{90}, and p_{99}) of the exposure ratio in both UL and DL for UC 1 in the Outdoor coverage scenario for all operators. In the sections below, we analyse the results for each environment separately.

6.2.1. Urban environment

In the urban environment, the maximum UL exposure ratio (p_{99}) is similar for all networks (all operators and unified) as it is dominated by the maximum output power of the mobile device. An urban environment is typically characterised by the presence of many buildings, resulting in less LoS conditions. Therefore, there are many locations where the mobile device is required to use full power to reach the BS. When considering the p_{50} and p_{90} values, the lowest UL exposure is obtained by Operator 1. This is due to the fact that Operator 1 uses the largest and most dense set of available BS locations from the extended list, which reduces the distance between the BS and the user and therefore reduces the UL exposure. However, comparing the UL p_{50} exposure ratio of the unified network to the value of Operator 1, a higher UL exposure for the unified network is observed. This is driven by the larger number of users that the unified network has to serve (sum of all users from all operators). In particular, results show that operator 1 can serve six users per available BS, while the unified network can serve only five users per BS with an average UL power higher than the one found in operator 1.

For all considered networks, the maximum DL exposure ratios (p_{90}, p_{99}) are a factor of 10 lower than the UL exposure ratio and approaching a factor of 100 for the average (p_{50}) value. The DL exposure ratio for the unified network and operator 1 are very similar due to a similar ratio between the served users and the available number of BS in the extended list (nearly 5 users/available BS). As the users of operators 2 and 3 are generally farther away from the BSs, their DL exposure ratios are lower compared to the unified network and the network of operator 1.

The overall exposure of the active users regardless of the operator is highly dominated by the UL exposure (the exposure from their own mobile device) because the UL exposure ratio is a factor of > 10 higher than the DL exposure ratio as mentioned above. In this case, a denser network, as provided by operator 1 or the unified network, is the preferred choice.

6.2.2. Suburban environment

In the suburban environment, the differences between the UL and DL ratios are similar to the urban environment (see Fig. 5). However, the average exposure ratios are half those of the urban scenario. Particularly, the UL exposure on 5G is ten-times lower in the suburban environment compared with the urban one, while the DL is only 2.5 times lower. For the DL, this is related to a generally larger distance between the BS and the users, while for the UL, it is determined by more LoS situations.

6.2.3. Rural environment

In the rural environment, there are generally more UL situations with high exposure, as shown in Fig. 5. Both p_{90} and p_{99} are at similar high levels. Also, the p_{50} values for UL exposure are five times higher than in the urban and suburban cases. This is related to larger distances between the BS and the users than in the other environments, whereas DL exposure levels in the rural environment are very similar to those in the suburban environment.

6.2.4. Network comparison

Comparing the unified network to the other networks, the unified network as well as the network of operator 1 only cause noticeably higher DL exposure in the urban environment due to the proximity of users in those dense BS networks, but not in the other environments. In the urban and suburban environments, the denser networks of operator 1 and the unified network help to reduce UL exposure (see Section 6.2.1). Due to the dominance of the UL exposure ratio over the DL exposure ratio, the unified network and the network of operator 1 result in the lowest overall exposure ratios.

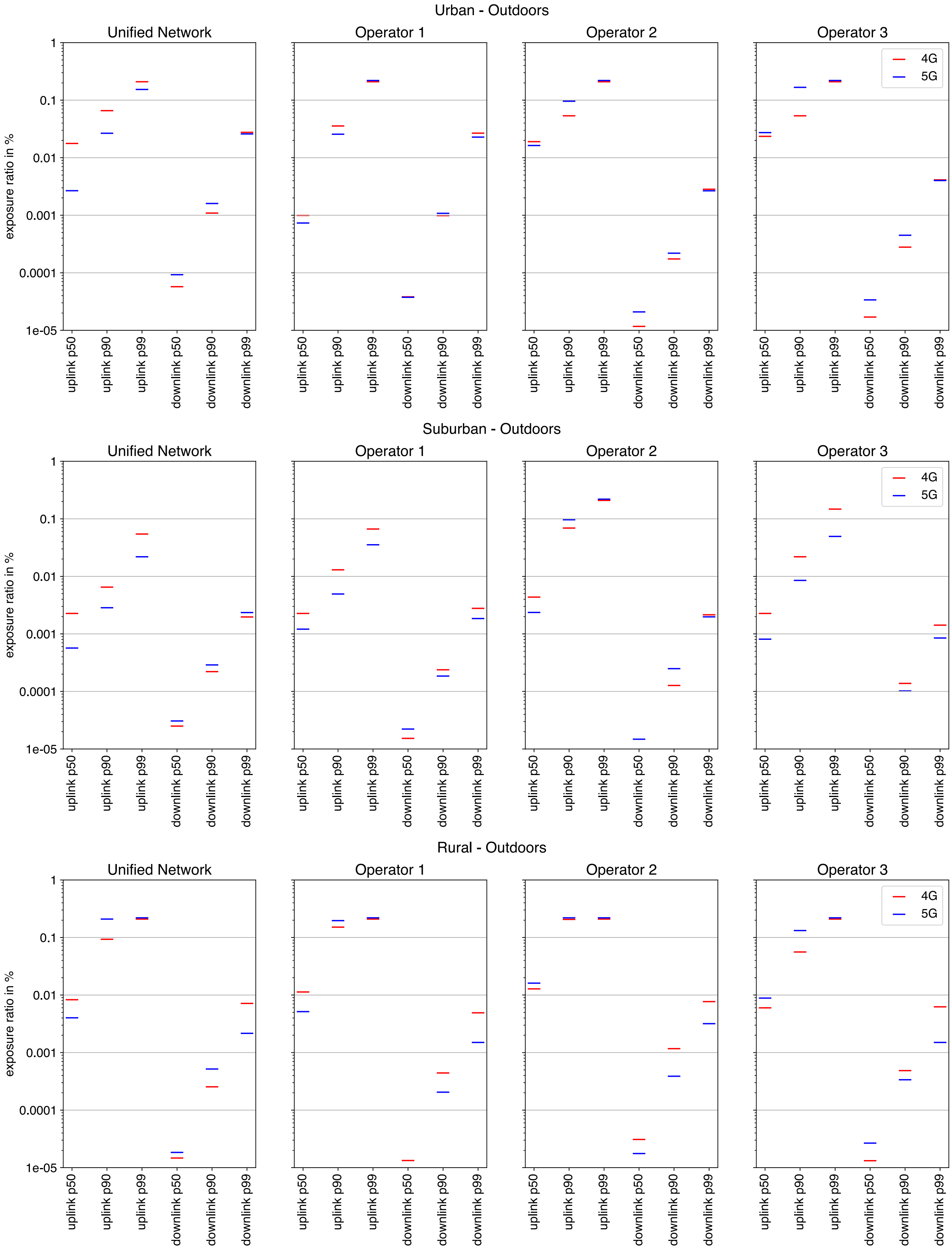


Fig. 5. Uplink and downlink exposure ratios between different operators and a unified network in the three different environments for use case 1.

6.3. Indoor and outdoor exposure

Table 12 summarise the exposure ratios for users in indoor and outdoor locations for the unified network in the urban environment in UC 1. DL exposure at outdoor locations increases by a factor 10 when comparing the outdoor only and indoor scenarios, due to the fact that indoor users need higher transmitted power that affects outdoor users. Furthermore, the results show that indoor exposure is always lower compared to outdoor exposure for indoor scenarios, due to the penetration losses in the building experienced by indoor users.

UL p_{90} and p_{99} exposure ratios are closer to the maximum level of $ER_{UL} \approx 0.2\%$. The average (p_{50}) exposure levels are in the same range for all scenarios and user locations. Outdoor users are generally subject to lower average (p_{50}) UL exposure ratios in 5G than in 4G (factor

Table 12
Exposure ratios for outdoor and indoor users in the unified network for use case 1. (Urban Environment.)

Tech	Location	ER_{UL}						ER_{DL}					
		Indoor users			Outdoor users			Indoor users			Outdoor users		
		p50	p90	p99	p50	p90	p99	p50	p90	p99	p50	p90	p99
4G	Indoor 15 m	$1.9e^{-5}$	$1.2e^{-4}$	$6.2e^{-4}$	$6.3e^{-5}$	$5.3e^{-4}$	$2.1e^{-3}$	$5.0e^{-6}$	$1.2e^{-4}$	$7.1e^{-3}$	$2.0e^{-6}$	$4.1e^{-5}$	$1.2e^{-3}$
	Indoor	$2.0e^{-3}$	$1.2e^{-4}$	$6.4e^{-4}$	$6.3e^{-5}$	$5.4e^{-4}$	$2.1e^{-3}$	$5.0e^{-6}$	$1.1e^{-4}$	$6.2e^{-3}$	$2.0e^{-6}$	$4.1e^{-5}$	$1.2e^{-3}$
	Outdoor	–	–	–	$1.7e^{-4}$	$6.6e^{-4}$	$2.1e^{-3}$	–	–	–	$1.0e^{-6}$	$1.1e^{-5}$	$2.8e^{-4}$
5G	Indoor 15 m	$9.0e^{-6}$	$9.2e^{-5}$	$7.6e^{-4}$	$2.5e^{-5}$	$2.5e^{-4}$	$1.4e^{-3}$	$4.0e^{-6}$	$8.1e^{-5}$	$5.1e^{-3}$	$2.0e^{-6}$	$4.4e^{-5}$	$1.0e^{-3}$
	Indoor	$9.0e^{-6}$	$9.4e^{-5}$	$7.5e^{-4}$	$2.5e^{-5}$	$2.5e^{-5}$	$1.5e^{-3}$	$4.0e^{-6}$	$8.1e^{-5}$	$4\text{-}9e^{-3}$	$2.0e^{-6}$	$4.6e^{-5}$	$1.1e^{-3}$
	Outdoor	–	–	–	$2.7e^{-5}$	$2.7e^{-4}$	$1.5e^{-3}$	–	–	–	$1.0e^{-6}$	$1.6e^{-5}$	$2.6e^{-4}$

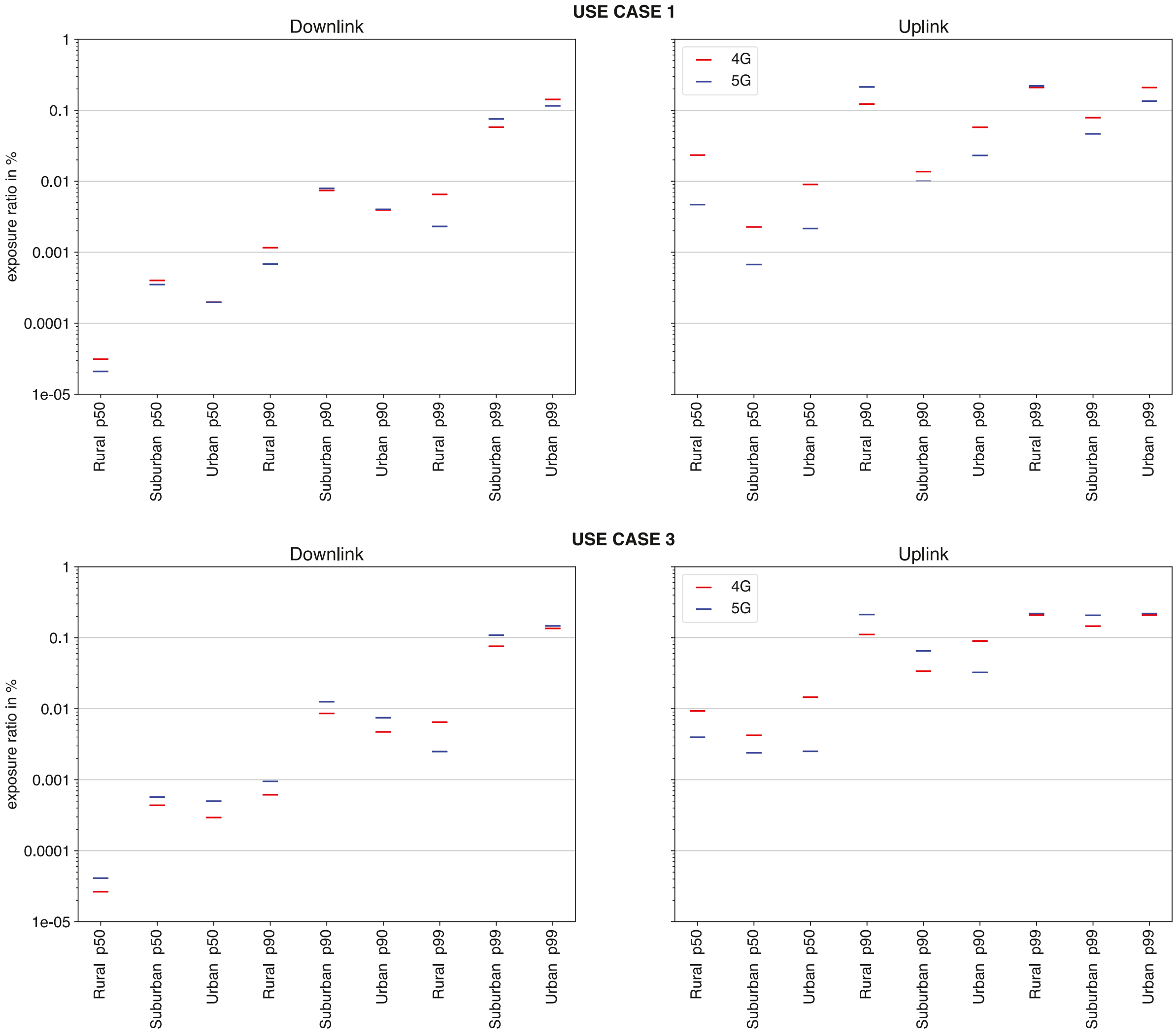


Fig. 6. Downlink and uplink exposure ratios in different environments for use case 1 and use case 3 in the unified network.

of 1.5 to 2), while in indoor locations the 5G UL exposure ratios are higher. This is due the fact that indoor users require higher transmission power to overcome the building penetrations losses leading to higher UL exposure values. Fig. 4 presents an example of a network solution for the indoor case, where BS and connected and unconnected users are shown.

In summary, for the indoor and outdoor scenarios planned, only the outdoor exposure of the DL is reduced for a network guaranteeing only outdoor coverage. However, based on the results presented in Section 6.1, a 5G outdoor-only network will also cover a significant portion of indoor locations. This conclusion is further supported by little differences between covering all and only small buildings. As the UL exposure is very similar in all coverage and data rate scenarios and dominant compared to the DL exposure, a separation of indoor and outdoor coverage does not result in a lower human exposure in the simulated scenarios.

6.4. Network quality and exposure

Fig. 6 shows the exposure ratios of UL and DL in terms of the data rate for UC1 and UC3. Comparing the DL exposure ratio for UC1 and UC3 shows similar result with a trend towards higher DL average p_{50}

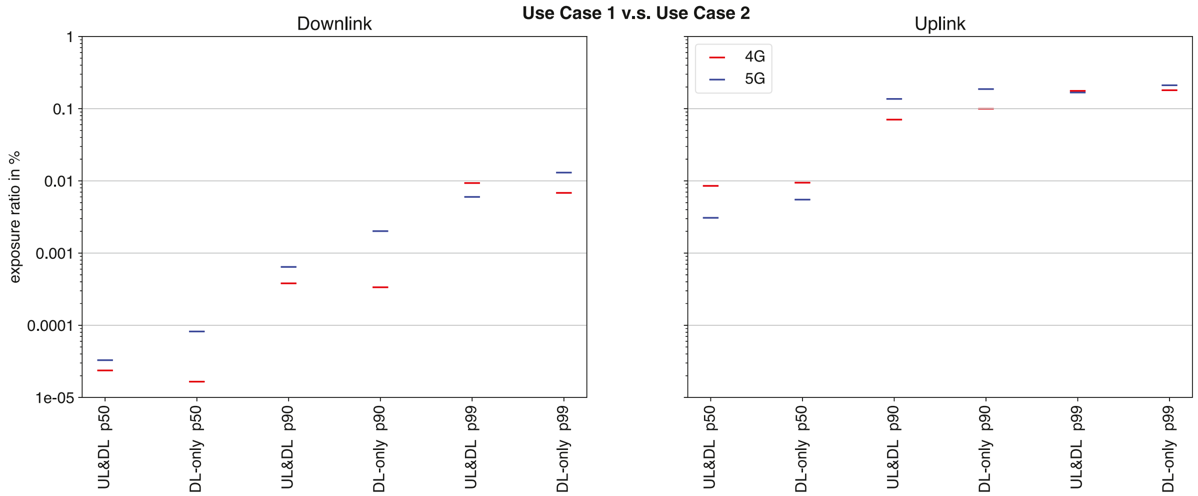


Fig. 7. Downlink and uplink exposure ratios for use case 1 (UL&DL) and use case 2 (DL-only).

exposure (+15% in 4G and +100% in 5G), due to the rise the number of used BS (42% in 4G and 25% in 5G) and the increase of transmitted power to support higher MCS in the UC 3. The largest increases in DL exposure can be found in the urban environment (+49% in 4G and +153% in 5G). The p_{99} levels of the DL exposure ratios are driven by the high exposure ratios of outdoor users in indoor scenarios.

The average UL exposure ratios for p_{50} in UC3 are 28% higher in 4G and 80% higher in 5G compared to UC1. For UC 3, the UL exposure is higher and approaching the maximum levels of the p_{90} value in suburban and urban environments. This effect is related to a higher required SNR and, thus, a higher mobile device output power.

6.5. Communication technology

Fig. 6 can also be used to compare the dependence of the exposure ratio on the communication system.

In the DL direction of the UC 1, there is no difference between 4G and 5G systems regarding the exposure level. Both systems result in approximately the same average (p_{50}) and peak (p_{90}, p_{99}) exposure ratios, since both systems use the same limit at the protection zones, leading to similar transmitted power regardless the technology. In the rural environment, there is a small trend towards lower exposure in 5G (−45%) for the UC 1 rate scenario. In the high data rate scenario, there is a trend towards higher DL exposure from the 5G network (+34% overall, 46% in the urban environment). Serving 1 Gbps brings the 5G network to its capacity limit and requires higher power levels to maintain the required SNR.

Regarding UL exposure, there is a trend towards a lower average (p_{50}) in the 5G network in UC 1 (−75%) and UC 3 (−61%). For p_{90} and p_{99} values, this effect is reduced and even reversed for UC 3 as the maximum UL exposure is mainly determined by the maximum output power of the mobile device.

6.6. Downlink-only optimisation

The DL only optimisation (use case 2) is defined to analyse exposure on non-connected users. Results presented in Fig. 7 show the effect on exposure to DL and UL when only the DL of the network is considered in the optimisation simulations. For 4G, the exposure to DL decreases (−30%), while for 5G, the exposure to DL actually increases (>100%). This is because, for 4G networks, omnidirectional antennas are considered aiming to reduce all the area exposure. On the other hand, for 5G networks using MaMIMO beamforming, the DL exposure of active users increases due to the spatial diversity of the system. In addition, the MaMIMO parts of the 5G network also require the UL information for a successful DL optimisation, leading to not optimal results.

Not surprisingly, the exposure to UL in UC2 is higher than in networks optimised for both UL and DL (UC1) (11% for 4G and 77% for 5G) on average. This is clear by the fact that UL is not optimised, and larger transmission power values are found. This means that for 5G networks, a multi-objective (UL and DL) optimisation is needed to reduce network exposure ratio.

6.7. Discussion with literature results

The presented results are delivered from the most advanced study on human exposure and realistic cellular network topology known by the authors. The exposure ratios observed in this study are of the same order of magnitude as the results reported in [17,18,33] where the exposure levels were estimated based on DL and UL signal strength measurements.

From a data network quality perspective, the 5G networks in this study were designed with a capacity ten times greater than that of the 4G networks. This increase in 5G capacity does not lead to a significant increase in DL exposure compared to 4G, as shown in [10,16]. Only in the scenarios with the highest data rate (UC3) did the exposure in the 5G DL networks increase by 34% on average in the three environments. In the UL direction, the use of 5G helped decrease the exposure by −75% in UC 1 and by −61% in UC 3.

7. Conclusions and future work

This study analysed UL and DL exposure ratios in various mobile communication network topologies. The main findings reveal that (i) human exposure is determined by an UL exposure ten higher than a DL exposure, (ii) deployment of a 5G infrastructure requires a BS infrastructure three times denser than 4G, (iii) 5G is able to provide a tenfold network data capacity for a similar or even lower human exposure than 4G and iv) when optimising networks for low human exposure, both the UL and DL always have to be considered. Our results show that it is not possible to design a network with a good data transmission quality by only optimising the DL exposure. The study demonstrated that future networks can be realised without an increase of precautionary limits in Switzerland, since the number of BSs is mostly driven by the data requirements and not by the exposure limits.

Finally, in the course of this study, we identified future work and research needs to fill the remaining knowledge gaps. In the future, the application of millimetre waves and its influence on human exposure should be analysed. In the present study, we applied harmonised, yet simplified models to analyse indoor exposure to mobile networks. To lower the uncertainties about exposure in indoor scenarios, additional indoor modelling would help to substantiate our results. They could further be strengthened by validation measurements in the UL and DL of 4G and 5G networks. Other areas of future research include the extension of the networks with distributed MaMIMO, mixed technology networks and as well as realistic movement of user.

CRediT authorship contribution statement

German Castellanos: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Simon De Gheselle:** Conceptualization, Methodology, Software, Formal analysis. **Luc Martens:** Funding acquisition, Review. **Niels Kuster:** Funding acquisition. **Wout Joseph:** Supervision, Writing – review & editing. **Margot Deruyck:** Methodology, Software, Writing – review & editing. **Sven Kuehn:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Margot Deruyck reports financial support was provided by Research Foundation Flanders. German Castellanos reports financial support was provided by Colombian School of Engineering Julio Garavito. German Castellanos reports financial support was provided by Swiss Federal Office of Communications (OFCOM).

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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