EASA – EUROCAE Framework Contract N°EASA.2016.FC19

Special Contract N° 2016-004

Deliverable N°1

HIRF requirements applicability to new urban flying vehicles

V 2.0.0

EUROCAE COMMUNICATION
9-23 rue Paul Lafargue "Le Triangle" building
93200 Saint-Denis, France
www.eurocae.net

Tel : +33 1 49 46 19 65

SARL au capital de 50 000 € - RCS Nanterre B 424 467 066
TVA intracommunautaire FR 51 424 467 066 - APE :7490B
Code SIRET : 424 467 066 000 25

Authoring & Approval

Prepared By		
Luc Deneufchâtel, Alain Valle & Marc Meyer	Technical experts	
Reviewed By		
Anna Guégan	TPM	
Approved By		
Christian Schleifer	Director	

Document History

Edition	Date	Status	Author	Justification
00.01.00		Draft	Alain Valle – Marc Meyer – Luc Deneufchatel	
00.07.00		Mature draft	Anna Guegan	
00.09.00		Final	Anna Guegan	
00.10.00		Comment review	Alain Valle – Marc Meyer – Luc Deneufchatel	
00.11.00		Final	Anna Guegan	
01.00.00		Approved	Christian Schleifer	
01.01.00		New comment review	Alain Valle – Marc Meyer – Luc Deneufchatel	
01.02.00		Final	Anna Guegan	
02.00.00		Approved	Christian Schleifer	

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. PRELIMINARY STUDY PURPOSE

In the framework of the establishment of special conditions (SC) for Vertical Take-Off and Landing platforms (VTOL), a EUROCAE subgroup (SG-4 of WG-112) is addressing specific aspects of flight, from environment to trajectories and flight controls. This activity includes the High Intensity Radiated Fields (HIRF) environment to be considered for the certification of these new types of airspace users; e.g. flying taxis, flights in an urban environment. Certification specifications (CS) and associated Acceptable Means of Compliance (AMC) for Unmanned Aircraft Systems (UAS) will also need to consider such elements as UAS are expected to operate close to the ground and in urban environment.

The preliminary study reported in this document aims to feed this reflection by assessing whether the present HIRF environments, defined in the 1990s for aircraft certification purpose, are still relevant for addressing urban air mobility (UAM) vehicles. It is also the opportunity to question whether the present HIRF environments are still applicable for aircraft certification, regarding the evolution of radio/radar emitter technologies and powers, and the new services performed by electromagnetic radio-frequency emission in the air.

This preliminary study will assess to what extent the present HIRF environments are relevant to address these evolutions and if a more-in-depth study, potentially involving aeronautical companies in a specific working group, is required to update the current regulation.

1.2. PRELIMINARY STUDY RATIONALE

Firstly, it will be assessed whether the present HIRF environments are still relevant for the certification of conventional fixed-wing aircraft and rotorcraft considering historic margins provided by the establishment logic of HIRF environments and the evolution of this HIRF environment. At this end, the evolution of the services performed by electromagnetic radio-frequency emission in the air (e.g. frequency bands and service deployment) and the power and technologies associated to band-driver emitters will be studied.

Secondly, an analysis shall identify HIRF environment drivers in urban and suburban areas where VTOL will operate. It will allow assessing to what extent the present HIRF regulation can comply and whether some more restrictive thresholds should be applied for VTOL considering some reasonable clearance distance from emitting sources. This preliminary study is focusing on the frequency range **where the electronic equipment items are known to be the most susceptible (typically below 5GHz)**.

Thirdly, since many band drivers are far or absent from cities and from typical VTOL routes (e.g. from airport to the city), possible relaxations should be considered as regard to present HIRF environments when it is constraining too much VTOL design. At this end, some mitigations means, e.g. area exclusion, could be relevant to minimize the weight and cost of platforms.

2. ORIGINS OF HIRF REGULATION

2.1. THE HISTORICAL SET UP OF HIRF REGULATION

In the past, the deficiency of electronic equipment robustness against HIRF unfortunately led to catastrophic events. Some of the most well-known accidents are mentioned here [12]:

- In 1967, the missile of a Combat Aircraft onboard US Aircraft Carrier Forrestal had been untimely triggered, causing 134 deaths, 161 injuries and more than 500M€ of damages. Improper mounting of shielded connector of missing wiring was suspected.
- In 1988, international agencies reported that an US Army Helicopter crashes caused by EMI when the helicopter flew too close to a powerful radar and radio emitters (22 deaths). Electronically controlled flight systems were suspected to be susceptible to HIRF environment.
- In 1984, a Tornado Fighter Aircraft crashed near Munich after flying too close to a powerful Voice Of America (VOA) High Frequency (HF) Band transmitter.
- In the automotive domain, malfunctions of early Antiblock Braking Systems (ABS) occurred when submitted to a severe HIRF environment leading to fatal accidents. Meshed screens were installed along some German Highway sections to attenuate electromagnetic field from nearby emitters. Now, a significant protection against HIRF is performed on safety related equipment, by bulk current injection (BCI) on harness and radiated field aggression in the same way than aeronautical equipment.

As a result, the need to implement a regulation frame for HIRF protection of critical electronical systems appeared crucial in the 1980s because of an increased risk due to:

- the wider use of electronic devices instead of mechanical mechanisms to ensure flight critical aircraft control systems,
- the increase of integrated circuit operating speed, potentially more susceptible,
- multiplication of RF emitters and increase of their power.

As a consequence, HIRF SC were established for A320 certification, the first fly by wire airplane. These SC were adapted in 1987 for AS355N certification (Full Authority Digital Engine Control (FADEC) disturbance leading to inflight engine shut down without specific hardening) and in 1990 for the evolution from Mark I to MKII of Super Puma (new critical functions with FADEC, Multi-function Display in Cockpit, digital Auto Pilot).

The Federal Aviation Administration (FAA) launched a committee to establish a HIRF environment with the support of the Society of Automotive Engineering (SAE). First, intermediate results were established in a draft NPA/NPRM with non-consolidated assumptions. This Interim Policy became JAA/EASA System Interim Policies 25/2, 23/1, 27-29/1, superseding initial national special conditions. This Interim policy has been made applicable by certification review item (CRI) before the update of the regulations (CS23.1308 Amendment 4, CS25.1317 Amendment 17, CS27/29.1317 Amendment 4).

Four environments have been calculated by the mandated European and American committees for civil aircraft flying under existing flight rules (e.g. Instrument and Visual) on the 10KHz - 40GHz frequency range. These environments were established on the basis of 500 000 emitters located in the US and Western Europe: Continental United States, Hawaii, Alaska, and Puerto Rico, plus the five participating European countries: United Kingdom, Germany, Sweden, France and the Netherlands.

These environments were built from emitters that are airborne, land-based, airport / heliport ground-based, off-shore platforms and ship-based following computation methods and assumptions which may be consulted in different reports [15] [1]. These environments are defined in the dedicated HIRF protection sections of AC20.158 rev. A [12] and AMC 20.158 [5], the guidance documents to answer FAR/CS23.1308, FAR/CS25.1317, FAR/CS27.1317 and FAR/CS29.1317 regulation [11]:

- fixed wing severe not present itself in HIRF regulations
- certification: Environment I
- Normal: Environment 2
- Rotorcraft severe: Environment 3

The following table highlights some performance criteria in regard of the HIRF environment and the associated main assumptions considered for the establishment of these environments as AMC20.158 [5] for system that performs a function whose failure would prevent the continued safe flight and landing of the aircraft (i.e. a failure condition is potentially catastrophic - Level A certification level).

TABLE 2.1-1: HIRF REFERENCE ENVIRONMENTS

Environment	Applicability and performance criteria	Specificity	Main assumptions
1	**Airplanes part 23 & 25** for systems whose failure would be catastrophic in **Visual Flight Rules (VFR)** operations **Rotorcraft part 27 & 29** for systems whose failure would be catastrophic in **Instrument Flight Rules (IFR)** operations Level A VFR/IFR **function** shall not be adversely affected during and after the exposure, and all electrical and electronic system contributing into this function shall automatically recover normal operation of that function, in a timely manner after the HIRF exposure.	Airplane design sizing	1000 feet slant distance (IFR) for non-airfield fixed transmitters
2	**Airplanes part 23 & 25** **Rotorcraft part 27 & 29** **Each electrical and electronic system ensuring a critical function** shall not be adversely affected during and after the exposure.	Airport environment = civil aircraft environment encountered during normal flight operations	Only air-field transmitters considered
3	**Rotorcraft part 27 & 29** for systems whose failure would be catastrophic in **Visual Flight Rules (VFR)** operations Level A VFR **function** shall not be adversely affected during and after the exposure	Rotorcraft design sizing	500 feet slant distance (VFR) for non-airfield fixed transmitters Off-shore platforms emitters (100 feet – direct)

Some performance criteria were also defined for equipment providing less critical functions (level B & C), considering lower HIRF levels as defined in AMC 20.158 [5].
In the certification process, compliance to the appropriate HIRF environments and levels must be demonstrated by an applicant for each electrical and electronic system for which functional failure would:

- prevent the continued safe flight and landing of the rotorcraft/airplane (Level A);
- significantly reduce the capability of the rotorcraft/airplane or the ability of the flight crew to respond to an adverse operating condition (Level B);
- reduce the capability of the rotorcraft/airplane or the ability of the flight crew to respond to an adverse operating condition (level C).

2.2. MARGINS INDUCED BY THE LOGIC OF HIRF ENVIRONMENT ESTABLISHMENT

The logic followed for the definition of the HIRF environments in the regulation preserved some margins as regard to the assumptions, e.g. the emitters considered and their distances from airplanes / rotorcrafts. Moreover, higher levels have been applied on some frequency bands for future transmitter developments in the final environments. This conservative strategy was also used because the global electromagnetic environment has been considered as changing and uncertain, since no data was available from nations not involved and potentially operating with high-power transmitters. In addition, it was considered more practicable to limit the subdivision in frequency bands of the overall HIRF frequency range.

Sources of margins are outlined below:

- The level of each band is driven by a few strong emitters called “band drivers”, significantly more powerful than the numerous emitters present in the band.
- The computations performed considered maximum peak power of the emitters, which do not operate continuously at their maximum output power level.
- For environment I, radar frequency range levels have been increased above the envelope obtained by computations from distance assumptions in order to cover future evolution considered at no cost. As a consequence, a 200V/m minimum average environment has been required in the whole radar frequency range (i.e. here above 1GHz).

This resulted in a margin resulting from this conservative process in daily operation with a full level exposition potentially rare and only in some frequency segments.

2.3. IMPACT ON EQUIPMENT DESIGN

The equipment protection against HIRF needs to implement hardware filtering (generally implemented on filtering board) and numeric filtering, especially to be immune to pulse mode levels present in the three presented environments. Moreover, equipment housing shall be faradized with appropriate radio frequency (RF) sealants and regular screws in order to limit the penetration of the electromagnetic (EM) field inside the housing and subsequent coupling on internal cabling, Printed Circuit Board (PCB) lines and micro-controllers. The severity of the environment to be withstood impacts the cost of the equipment. Increased costs will also result from the technology solutions to be implemented and from the duration of equipment development, in the event a redesign is required following unsuccessful HIRF qualification tests.

It should be noticed that the HIRF protection weakness of equipment may be compensated to a certain extent (10dB to 20dB according faradization effort, e.g. RF conductive seals) by faradized equipment bays. However, these solutions present drawbacks with a significant impact on cost, integration and maintenance (the effectiveness of such solution has to be demonstrated over the whole aircraft lifecycle).

Rotorcraft manufacturers and, to a lesser extent, civil aircraft manufacturers experimented design and qualification issues for build-on-spec equipment items development, and then further with equipment suppliers. Less severe impact is noted for civil aircraft manufacturers due to a less severe environment (Environment I instead of Environment 3), a better faradization of the airplane fuselage and a wider use of avionic bays.

Reaching such requirement levels is not trivial and is definitively a main driver of the design and therefore the use of non-aeronautical Commercial-Off-The-Shelf (COTS) equipment for functions critical for flight and landing is impossible.

The experience in HIRF equipment qualification tests following ED-14 / DO-160 section 20 [8] evidenced that most of equipment upsets occur in the 100MHz-5GHz frequency range. Above that range, the susceptibilities are rare but not excluded, especially when the equipment have circuits operating at higher levels, as mentioned in AC20.158 [12] and ED-107A / ARP5583A [7]. This was consistently confirmed by a recent study performed by aircraft and equipment manufacturers [17][15]. In addition, these regulatory guides state that aircraft and system tests are not to be performed for the HIRF environment above 18 GHz, if data and design analysis show the integrated system test results satisfy the requirement from 12 to 18GHz, and if the systems have no circuits operating in the 18 to 40 GHz frequency range.

Another frequency range positioned between 2MHz and 100 MHz is challenging and impacting for the design of HIRF protection at rotorcraft level because leading to area faradization and cable over shielding. Because this frequency range corresponds to the typical structure and cable resonance frequencies which tend to increase coupling levels on this frequency range and reinforce EM protection's need to comply with the HIRF environments. Indeed the level is 200V/m for rotorcraft and it shall be noticed that the level on 30-100MHz band is historically based on the level of high power HF transmitting antennas (2-30MHz). Maintaining the same severity may be reconsidered since the significant impact discussed above. Beside, these HF antennas are very rare (not more than a few by country and some have disappeared, e.g. voice of America emitter in Germany, an emitter in Sweden; only a few emitters remains such as the radio Vatican transmitter).

2.4. IMPACT ON AIRCRAFT AND HELICOPTER DESIGN AND CERTIFICATION PROCESS

The severity of HIRF environments implies many constraints on electrical systems integration and on the design of electrical equipment items. The HIRF protection is more sizing on rotorcraft because of the inherent characteristics of an helicopter which presents a poor faradization in cockpit and cabin compared to an aircraft fuselage and also because many critical equipment's routes are installed externally. Therefore no attenuation is considered on the Environment III for the rotorcraft equipment qualification on the contrary to many aircraft equipment items. Another evident reason is that intrinsically the levels of environment III for rotorcraft are more severe than in environment I (around 6dB).

At the level of aircraft, cable over-shielding with proper terminations shall be installed where harnesses are routed externally or where faradization brought by the external skin is limited (e.g. with non-conductive covers such as glass material). Then, this protection leads to an additional weight and cost dedicated to HIRF protection.

This impact is all the more detrimental on UAM VTOLs which are propelled by electric and hybrid engines, and for which weight is crucial to reach full performance (autonomy) to fulfil the mission.

3. RADIO ELECTRIC ENVIRONMENT EVOLUTION

3.1. GENERAL APPROACH METHODOLOGY

This chapter intends to provide a qualitative assessment of the RF environmental evolutions since the initial selection of the various HIRF levels associated with HIRF frequency bands.

It is assumed that no significant changes have taken place regarding the nature of the operations of conventional aircraft and rotorcraft. This leads to the fact that the minimum distances to the HIRF sources are those used for the establishment of the three HIRF environments.

It is also assumed that no significant changes have taken place regarding the potential high-power field threats that could be generated by other aircraft close to the victim one. These cases were considered in the elaboration of scenario leading to the initial HIRF environment definition.

Therefore, the following assessment is only focusing on the changes of the RF environment outside of the aircraft themselves.

3.1.1. Association between HIRF frequency bands and International Telecommunication (ITU) services operating in these bands

The HIRF level tables presented in ANNEX 2: AMC20.158 - HIRF environments have been structured using a sequential frequency segmentation of the usable spectrum in 17 sub bands. Unfortunately, this segmentation did not take into account the nature of the ITU services operating in these frequency bands (from an ITU point of view).

At ITU level, a spectrum allocation is not associated with a system but with a service. The main services from the ITU Radio Regulation considered are listed in ANNEX 3. Therefore to monitor the evolutions of the radio electric environment since the start of the HIRF framework, it is essential to identify the relevant services that must be analysed for each frequency band.

The following subset of services from the ITU list are considered relevant regarding HIRF:

- Fixed service
- Broadcasting service
- Radio-location service
- Radio-determination service
- Maritime radio and navigation services
- Radio-navigation service
- Industrial, Scientific and Medical (ISM) applications service
- Meteorological aids service
- Maritime mobile service
- Land mobile service
- Mobile satellite service
- Fixed satellite service
- Land mobile satellite service
- Maritime mobile satellite service

In the HIRF establishment, the following systems (not to be confused with services) have been considered in the following reference environments:

- in airport environment: Instrument Landing System (ILS, such as localiser, glide path and markers), Distance Measuring Equipment (DME), Tactical Air Navigation beacon (TACAN), Very and Ultra High Frequency (VHF/UHF) transmitters, VHF Omni-Directional Range (VOR), airport surface radar, approach radar, en-route radar and weather radar;
- in heliport environment: VOR, DME, VHF/UHF transmitters, satellite transmitter, Heliport surface radar and weather radar
- in ship-based environment: TACAN, VHF/UHF transmitters, satellite transmitter air search radar, ground search radar and weather radar;
- in a general ground-based environment: Amplitude Modulation (AM), HF, Frequency Modulation (FM) radio broadcast, Television (TV) broadcast, submarine communications, land mobile communications, satellite up links, VHF / UHF communications, en-route surveillance radar, weather radar, defense radar, Loran transmitters, troposcatter and astronomy radar

As clearly indicated in the HIRF requirements, two types of threats are to be considered:

- The continuous average field radiation
- The pulsed field radiation

These two threats could, for a given HIRF frequency band, involved two trigger ITU services.

These potential contributing services are split into two categories:

The first category, that constitutes the major threat, is constituted of services requiring ground based high power transmitters. They include the following:

a) The Radio and TV broadcast services (high radiated power omnidirectional and continuous transmission).

b) The radar infrastructure mainly used for non-cooperative targets (“primary” radar using the reflected signal from the target); these systems are generally using pulsed wave form with low duty cycle (pulse duration rather short).

c) The radio link supporting the “fixed services” with transmitters using usually high directivity antennas for point to point links.

The second category, that constitutes a lower threat, is constituted of services involving ground based medium to low power transmitters. They include the following:

a) The mobile services in general[1] (i.e. mainly ground base stations) that are also developing rapidly in a large part of the spectrum

b) The earth stations for satellite connection (i.e. feeder links). They must be considered due to the high antenna gain that is used to achieve the required power budget.

TABLE 3.1.1-1 summarises the hierarchy of ITU services in terms of HIRF impact using three ranks.

Rank 1: Services are the most significant one in terms of effective radiated power.

Rank 2: Services would have a more limited impact except in the case of new flight operations much closer to the “base station”.

Rank 3: Service could be relevant in the new context of operation around cities due to the usage of high gain antenna.

[1] Aeronautical services are not considered here as far as they belong to the normal environment of aircraft operations.

TABLE 3.1.1-1: MAJOR ITU CONTRIBUTOR TO HIRF THREAT

ITU Service	HIRF relevance rank	Associated technology family
Fixed service	1	Radio link (high directivity antenna)
Broadcasting service	1	High power continuous transmitter
Radio-location service	1	Radar pulsed transmission
Radio-determination service	1	Radar pulsed transmission
Maritime mobile service	2	Base station transmitter
Land mobile service	2	Base station transmitter
Meteorological aids service	2	Radar wind profiler
Fixed satellite service	2	Feeder link ground transmitter
Industrial, Scientific and Medical (ISM)	3	Continuous transmission
Mobile satellite service	3	Feeder link ground transmitter
Land mobile satellite service	3	Feeder link ground transmitter
Maritime mobile satellite service	3	Feeder link ground transmitter
Maritime radionavigation service	3	Base station transmitter
Radio-navigation service	3	Base station transmitter

3.1.2. Association between HIRF frequency bands and ITU services

After establishing the association between HIRF frequency bands and the relevant ITU services, the following analysis will be applied:

1. For each HIRF frequency band identification of the **trigger ITU service**[2],
2. Assessment of the evolution of the identified service since the starting point 30 year ago. This assessment is an expert judgment qualitative approach based upon:
   - the consideration of the general evolution of the concerned ITU service
   - the consideration of the general technology evolutions.

   This twofold assessment is further detailed in the section 3.2.
3. Summary of the HIRF environment evolution in a table indicating the nature of the evolution with only three areas: lower threat, stable threat, potential higher threat (than the one identified 30 years ago).

TABLE 3.1.2 summarises the result of this process, identifying the ITU service that constitute the threat trigger per HIRF frequency band. For some HIRF frequency bands several ITU trigger services can be found corresponding to the pulsed case or to the average case.

[2] By “trigger ITU service”, we mean that this ITU service is generating higher threat than other ITU services operating within the HIRF frequency sub band.

TABLE 3.1.2: MAIN ITU SERVICE CONTRIBUTOR PER HIRF SUB-BAND

HIRF FREQUENCY BAND	ITU TRIGGER SERVICE
10 kHz - 100 kHz	Mobile maritime
100 kHz - 500 kHz	Broadcast – Fixed link with submarine Loran C
500 kHz - 2 MHz	Broadcast (fixed radio)
2 MHz - 30 MHz	Broadcast (short wave radio)
30 MHz - 70 MHz	Broadcast fixed TV
70 MHz - 100 MHz	Broadcast (FM radio)
100 MHz - 200 MHz	Broadcast TV
200 MHz - 400 MHz	Broadcast TV
400 MHz - 700 MHz	Broadcast TV
700 MHz - 1 GHz	Radio determination (ship based) Broadcast TV
1 GHz - 2 GHz	Radio location (ATC radar) Satellite feeder link
2 GHz - 4 GHz	Radio location Meteorological radar
4 GHz - 6 GHz	Radiodetermination Fixed satellite
6 GHz - 8 GHz	Fixed satellite Spread spectrum
8 GHz - 12 GHz	Fixed satellite Tracking radar Precision Approach Radar
12 GHz - 18 GHz	Fixed satellite Airport surveillance radar
18 GHz - 40 GHz	Satellite communication Airport radar

According to the methodology, for each HIRF frequency sub band, the selected HIRF levels apply in the entire HIRF frequency sub band. In practice, the trigger ITU service (and the corresponding ground transmitters) is only operating in a part of the band (generally a limited one).

The direct consequence of the simplified approach used in the HIRF domain created significant margins in the remaining part of the HIRF frequency sub band, because the ITU service operating in this remaining part generated much lower RF threat level.

To take an example, in the HIRF frequency sub band from 1 GHz to 2 GHz, the trigger ITU service is the “radiolocation service” (mainly constituted of ground based primary surveillance radars) that are operating in less than 25% of the HIRF frequency sub band. As a result, it generates a high level of protection against the other ITU services that operate within 75% of this HIRF frequency sub band. Thus, significant margin is indeed provided within the overall spectrum.

3.2. ITU SERVICES AND ASSOCIATED TECHNOLOGY EVOLUTIONS AND IMPACT ON THE RADIO ELECTRICAL ENVIRONMENT

Based upon the finding of the previous step (i.e. TABLE 3.1.2), the approach followed in this section consists in an overall analysis of the changes in terms of:

- ITU service usage (some existing services are about to completely disappear like Medium Frequency (MF) and HF radio broadcast);
- ITU (or regional organisation linked with ITU) actions intending to control the deployment of new services, or new system for a given service, to ensure they do not create new threat against existing operations;
- Supporting technology changes for the relevant ITU services (e.g. Radiolocation or Broadcast);
- Emerging new services in the higher part of the spectrum (i.e. above 15 GHz).

3.2.1. "Trigger" ITU services evolutions and associated protection activities

One of the major evolutions during the last 30 years is the increased awareness of the limitations of the usable spectrum and the need to share spectrum between services.

Increasing awareness of the reality of interferences between services and system had led to restrict as much as possible transmitter power. The major effect led to the usage of sophisticated signal processing technics at receiving level instead of continuously increasing the transmitted power.
In addition, the rising societal concern regarding human health threats associated with continuous radio frequency has led to the need to limit the exposure risk, even though current study and expert analysis have not yet proved the consistency of such threats. As a first result, mobile phone manufacturing industry were required to demonstrate that their user's equipment (i.e. smartphone) complies with a new indicator, the Specific Absorption Rate (SAR)[3] as an answer to this fear among the society.

Such move had also an impact on base stations that must also respect a maximum radiated field to protect human being in their vicinity.

We can expect that in a context of global concern of potential harmful health impact from radio frequency transmitters, more restrictions will be enforced to respond to society apprehension, regardless of scientific evidences.

3.2.1.1. European Conference of Postal and Telecommunications Administrations (CEPT) initiative

Under a proactive French proposal, CEPT decided to contribute in maintaining the safety level that HIRF regulation provided by setting up recommended practices to its European member states to ensure that the growing deployment of new systems will respect the overall levels specified within the HIRF regulation. The specific case addressed is the satellite earth stations located around airports and the initiative identified the appropriate scenario of station overflying to keep the protection effective.

This initiative has led to the publication of the CEPT ECC report 066 [3] for the benefit of national spectrum regulatory agencies to control the new deployment of satellite ground earth station nearby airport, in order to keep their threat level to aircraft below the levels defined per frequency sub band in the HIRF framework.

This initiative from CEPT is very welcome if we consider that the development of satellite communications is growing and is also distributed within a large part of the spectrum above 1 GHz. This is a *de facto* additional safety measure that increases the protection of aircraft operations (at low altitude nearby airports).

---

[3] Today SAR maximum level are 2 W/kg in Europe and 1.6 W/kg in the USA (but the demonstration cases are slighthly different between the two continents)

3.2.1.2. ITU Trigger Service evolutions

3.2.1.2.1. Broadcast services:

a) Radio broadcast:

Historically, every State has developed its own radio broadcast infrastructure in order to promote its society values and to maintain a certain influence on the largest possible community. To that effect the radio broadcast network[4] was operating in several frequency bands that permitted to increase their coverage area. The main characteristic of such service was the high radiated power in a continuous mode and with omnidirectional antenna patterns.

They were one of the most severe sources of RF threats for aviation.

In a large part of the lower spectrum (i.e. below 400 MHz), the transmitters associated to such network appear as the higher contributors in terms of aircraft system threat and were selected as the “trigger” to set up the HIRF associated levels.

Significant changes took place during the last 30 years, in terms of State influence that *de facto* quickly eclipsed the former radio broadcast instrument. Among them the major ones are:

- The very rapid development of Internet and the emergence of new media to touch and influence a large worldwide community (e.g. social network supported by the Internet technology – Facebook, Twitter...);
- The broadcast of TV programmes using internet infrastructure, various mobile telephony networks or satellite distribution and broadcast capabilities.

The result of these drastic evolution is that the historical radio broadcast for long range coverage (Short Wave, Medium Wave and Long Wave) has been drastically reduced everywhere. In parallel, the transmitter power level was significantly reduced considering the strategical changes mentioned above.

As a conclusion, the HIRF levels, within this part of the spectrum below 400 MHz, present a higher safety margin compared to 30 years ago. The trend in the future is going in the same direction leading to the fact that the “Broadcast” service in the lower part of the spectrum will not be anymore the trigger ITU service.

For the other radio broadcast services, the evolution was pushed by the deregulation and the wide increase of radio operators. This evolution had pushed to improve the existing technology to cope with the spectrum constraints generated by the emergence of more radio broadcasters.

b) TV broadcast

TV broadcasts have also significantly evolved during the last 30 years. The number of TV operators has significantly increased, especially in a deregulated competition context. This move led to a review of the spectrum usage and allocation, thus inducing major technological changes.

3.2.1.2.2. Satellite based services:

During the last 30 years, satellite-based services have developed to satisfy a growing need for communication, mobility and continuous data exchanges.

The historical services dealing with satellite-based services have been revisited to accommodate new entrants, pushing for more efficient spectrum usage. Here again the spectrum constraints have pushed industry to improve the technology in a way

[4] Voice of America is a good example of such networks.

that, on average, the power of transmitters was reduced to limit interference constraints.

Parallel initiative, such as CEPT's ECC report 066 described above, had led to a better control of the system operating in these ITU service frequency bands.

3.2.1.2.3. Radio-location & Radio-determination

Historically, radar system to support surveillance needs used high power transmitters. This is particularly true when the surveillance mission was not supported by target cooperation. In such a case, detection of any target is associated with the signal received at the ground station from the reflection on the target itself.

Depending on the nature and structure of the target, the reflection signal could not always be sufficient to allow detection: furtive technology was quickly developed in the military domain to avoid detection by classical radar simply using the reflected signal.

The spectrum demand, generated by the explosion of the need for continuous mobile connectivity and exchanges, had several impacts on the historical spectrum allocation to the various services. Then spectrum sharing principle created significant changes in the design of related technologies. This is particularly true for radio-location and radio-determination services.

On one hand, the system using the frequency band allocated to these services are characterised by high power and high directivity in their transmission. On the other hand, the receiver is using very low-level signal, sometimes hidden in the background noise. Therefore, when located close to the ground transmitter, the receiver equipment will suffer from high level interreferences. The only mitigation means of such interference was to require minimum distance between the two systems.

3.2.1.2.4. Fixed services:

Despite the development of ground-based network using optical fibre technology, progressively replacing coper line technology, the use of radio link to provide point to point connection is still a core constituent of communication networks.

Fixed services are using several frequency bands in the spectrum up to 70 GHz.

The characteristics of such services are mainly the provision of a point to point connection using high directivity antennas at both ends. The transmitter power itself is not necessarily high, depending on the length of the link and the frequency band of operation.

The spectrum available for these services is limited due to its intensive usage. There is no significant evolution foreseen in the usage of such services.

In this domain the scarcity of spectrum resources had also led the industry to improve the spectrum efficiency and to review power budget through the introduction of advanced signal processing, to reduce the overall transmitted power.

3.2.1.3. Technology evolution

This section addresses the evolution of the technologies that are used to support the ITU trigger services. This is assessed using the same logic than the previous section.

3.2.1.3.1. Broadcast services:

a) Radio broadcast:

The first side effect of this major change has been the progressive removal of long-range radio broadcast used to promote national culture and influence (Voice of America or European national radio broadcast in various frequency bands). This is an important evolution if we consider that the major sources of high intensity radiation below 500 MHz were those long-range radio broadcast transmitters

Radio broadcast services have not disappeared completely. The remaining services have not the same operational objectives and are not generating the same RF threat. Digitalisation had been implemented and the migration is ongoing or completed everywhere.

As a good example, the power of a HF-band broadcasting transmitter near Bucharest (Romania) has been reduced to eliminate some EM disturbances in its vicinity.

Nevertheless, in some frequency bands, long-range radio communication services are still present without significant technology changes (i.e. mobile submarine telecommunication).

For these remaining services, the technology has drastically evolved moving away from high power tube technology to solid state technology. In parallel for spectrum efficiency reasons, the wave form has change to provide higher transmission quality with reduced power budget.

This means that in this service domain the technology has brought significant margin regarding HIRF consideration as far as globally the RF threats have been reduced.

b) <u>TV broadcast</u>

Due to the requirement to be spectrum efficient, fundamental technology changes were necessary. This has led to use more powerful wave form (i.e. Orthogonal Frequency-Division Multiplexing - OFDM) and signal coding to improve the end-to-end distribution quality and to reduce the transmitter power in parallel.

This technology transition is not yet completed everywhere, but the trend is moving in a good direction regarding HIRF impact. In the frequency band where “Broadcast” is a “trigger” service, this results in a significant increase of the effective safety margins. The evolution from analogic to numeric broadcasting led to reduce the power of transmitter, e.g. the power of the Limeux TV broadcast station, that is the most powerful TV station of this area near Amiens (France), has been reduced from 350KW down to 80KW. This station is located at a significant distance of main cities (Amiens or Abbeville).

3.2.1.3.2. <u>Satellite based services:</u>

The evolution of the technology in the domain of feeder links from ground earth station to satellite had been significant through the improvement of the wave form and the information coding in order to operate with much more optimised power budget.

But in this domain the major unchanged characteristic is the high directivity of ground-based antenna and the very limited exposition factor (the antenna main beam width is often less than 5°). There is no significant change that could impact negatively the HIRF existing levels that could be due to such service.

As mentioned above the new deployment of systems associated with these services are subject to a demonstration of compliance with the CEPT requirements that are translated indeed from the HIRF threshold applicable to the relevant frequency bands.

3.2.1.3.3. <u>Radio-location & Radio-determination</u>

The systematic usage of solid-state technology as a key transmitter evolution within the radar domain has led to a complete review of the design of the new radar families.

The first impact was on the radar mission in terms of radio-location especially in the military domain. Instead of continuously increasing the power transmitted from the ground-based radar (using both transmitter power and antenna directivity) industry was forced to consider technological alternatives. Powerful signal processing algorithm has emerged as an appropriate mitigation mean.

Following the military move towards more digitalisation and signal processing technics instead of running up with transmitted power, similar changes started to take place for all the radar applications including the cooperative radar (where targets cooperate to be detected and identified).

Among the significant evolution of the technology supporting this domain, the power reduction of the transmitter was compensated by:

- using more advanced signal processing;
- using larger pulse duration up to 10 time larger than the old technology (i.e. 40 to 100µs) that was not achievable with the old progressive wave tube technology. Such evolution could mean that the exposure time to the threat could be multiply by a factor 10.[5]

3.2.1.3.4. <u>Fixed services:</u>

Fixed services deployment has progressed continuously during the last 30 years using service allocations spread over the entire spectrum range.

These services are mainly constituted of radio links infrastructure that provide a network of point-to-point links. This means that the technology is using high directivity antenna with gain that can be up to 40db. Therefore, the exposure window will be very short for a conventional aircraft due to its velocity while it could be more severe for a helicopter during stationary operations.

The urban new entrants' operations within city area should be investigated later in this document to ensure that some specific cases are not creating new threats. We must keep in mind that such specific cases could be covered by the setup of restricted areas if necessary.

3.2.2. Considerations regarding some "Non trigger" ITU services

The rapid and continuous deployment of mobile telephony services from Global System for Mobile (GSM) to 5G, including the development of short-range communication technology should be considered in the context of emerging new operations within the high population-density urban environment.

The increasing need of citizens for continuous connectivity to ensure high quality communication in mobility has led to the deployment of complex ground-based networks with various types of architecture regarding the size of cells. In rural area, the network was typically using large-range antenna base stations; while in urban area, the topology required smaller cell dimension and significant densification of the base stations. This led to the development of smaller cells with base station with medium to rather short-range objectives.

The main driver for such evolution was also the need to protect human beings against the adverse effect of radiated field. Such arising awareness led to this new architecture proposal that will be the baseline for future urban mobile telephony deployment. The objective generally agreed by the mobile telephony service providers and the regulators is that the exposure level for human being should not exceed 3 V/m in the vicinity of the base stations.

This new architecture will be constituted by a mixture of components to cope with the high-density urban context of use of the mobile network. The relay antennas cover various cell's size, depending on their characteristics. They can be summarised as follows [1]:

- <u>Long range antennas</u>: powers of more than 6.3 W; This class of antennas is used for the usual network of operators; these antennas cover large cells:

[5] The HIRF requirements don't define the threat with this level of detail but it could be important for aeronautical industry to be aware of these evolutions because electronics is sensitive to the peak but also to the length of threat, as function of hardware and software electronic filtering strategy applied on the equipment design.

several hundred meters in urban areas and several kilometres in rural areas, and are also referred to as "macrocells";

- Medium range antennas: powers between 0.25 W and 6.3 W per port; This class of antenna corresponds to transmitters intended to be used outside, e.g. on street furniture; They serve "microcells", whose size varies from a few tens to a few hundred meters;
- Local coverage antennas: powers between 0.1 W and 0.25 W; This class of antennas is used to improve the coverage inside buildings, for example in shopping centres, business offices or car parks;
- Residential coverage antennas: powers below 0.1 W; This class provides connectivity to devices used in private homes ("femtocells"), with coverage comparable to WIFI boxes of internet service providers.

Long-range antennas constitute the core components of current networks. They are usually installed on high points, such as pylons or roofs of buildings in urban areas. These antennas are directional. A long-range site thus generally carries three antennas oriented in three sectors ensuring a 360° coverage. To focus their power, these antennas show gains of the order of 17 db. The typical maximum powers of these antennas vary between 40 W and 80 W, depending on the technology. For each beam, several antennas may be implemented to provide different services in the different frequency bands: 2G in the 900 MHz or 1800 MHz bands, 3G in the 900 MHz bands, or 2100 MHz and 4G in the 700 MHz, 800 MHz, 1 800 MHz, 2 100 MHz or 2 600 MHz bands.

A recent study conducted by national regulators indicated that the deployment of these smaller coverage base stations (medium to local antenna) induces a very limited field strength increase on top of the main component generated by the large coverage base station antenna [1];

Regarding the medium size antenna that will be deployed in urban areas, the exposure level of human being standing very close to the antenna remains below the agreed safe level of 3 V/m (i.e. between 0.7 and 2.7 V/m according to the ANFR study referred above).

Such evolution will ensure that the potential interference threat generated by the mobile telephony service in urban area will be well controlled thanks to the deployment of such lower range antennas.

Regarding the services that are part of the aircraft operations (e.g. Satcom on airplane, C2/C3 data links systems for drones), they are de facto considered within the certification framework as constituents of the aircraft itself.

3.3 HIRF ENVIRONMENT EVOLUTION SYNTHESIS

TABLE 3.2.2 below provides a synthesis of the evolution of the HIRF environment since its set up 30 years ago. As a direct result, it does not seem that a revision of the current HIRF levels for the three cases (certification case, nominal case and most severe case) is necessary. No environmental evolution addressed in this study justifies more stringent requirements.

The colours in the table provide a distinction between three ranks of ITU services:

Rank 1: Services are the most significant one in terms of effective radiated power.

Rank 2: Services would have a more limited impact except in the case of new flight operations much closer to the “base station”.

Rank 3: Service could be relevant in the new context of operation around cities due to the usage of high gain antenna.

TABLE 3.2.2: HIRF REFERENCE ENVIRONMENT EVOLUTION SYNTHESIS

HIRF FREQUENCY BAND	ITU TRIGGER SERVICE
10 kHz - 100 kHz	Broadcast
100 kHz - 500 kHz	Broadcast – Communication link with submarines Loran C transmitter
500 kHz - 2 MHz	Broadcast (fixed radio)
2 MHz - 30 MHz	Broadcast (short wave radio)
30 MHz - 70 MHz	Broadcast fixed TV
70 MHz - 100 MHz	Broadcast (FM radio)
100 MHz - 200 MHz	Broadcast TV
200 MHz - 400 MHz	Broadcast TV
400 MHz - 700 MHz	Broadcast TV
700 MHz - 1 GHz	Radio determination (ship based) Broadcast TV
1 GHz - 2 GHz	Radio location (ATC radar) Satellite feeder link
2 GHz - 4 GHz	Radio location Meteorological radar
4 GHz - 6 GHz	Radiodetermination Fixed satellite
6 GHz - 8 GHz	Fixed satellite Spread spectrum
8 GHz - 12 GHz	Fixed satellite Tracking radar Precision Approach Radar
12 GHz - 18 GHz	Fixed satellite Airport surveillance radar
18 GHz - 40 GHz	Satellite communication Airport radar

3.3.1 Increase of safety margin:

This increase of safety margin is highlighted in green.

This is true for the services within the frequency band from 500 kHz up to 1 GHz, due to the evolution of the broadcast services.

It is also true for the higher part of the spectrum (i.e. above 4 to 5 GHz), due to the lower influence on the aircraft avionics and systems.

3.3.2 Stability of safety margin:

When the environment evolution has been very limited, the safety margin is not changed. This situation is highlighted in yellow.

This is true for all the bands between 1 GHz and 4 GHz, in which many types of surveillance radar are operating, even if we can consider that technologies have improved during the last thirty years.

But it must be noted that the technology changes have not yet been implemented everywhere.

4. NEW FLYING VEHICLES AND OPERATIONS AND HIRF APPLICABILITY

In this chapter a presentation of the new platforms and vehicles is proposed. Then a synthesis of the nature of the new resulting missions is provided in order to identify the operational proximity of the vehicle regarding urban infrastructure and equipment.

An assessment of the HIRF specific environment is then made in order to identify the major HIRF sources that belong to such environment.

A specific analysis is also performed to address the mobile phone ground infrastructure in city areas and to investigate potential multi-sources threat (e.g. several base stations and multiple mobile phones) around the vehicle during critical operation.

Finally, this chapter reviews the suitability of the existing HIRF environments to cover the new urban operations and to prepare the main recommendations that will be presented in chapter 5.

4.1. DEFINITION OF THE NEW PLATFORMS AND MISSIONS

The intent of this section is to provide a description of the new platforms and their missions, as they will be operating in the new operational environments considered in the HIRF study: closer to the ground and in urban areas.

Such platforms are mainly Unmanned Aircraft (UA) and VTOL aircraft. Definition and classical Missions are described in the following sections.

4.1.1. Unmanned Aircraft

An Unmanned Aircraft (UA) is the flying component of an Unmanned Aircraft System (UAS). The UA, or Remotely Piloted Aircraft System (RPAS) according to the ICAO definition, is controlled by a Remote Pilot (RP) from a Remote Pilot Station (RPS) via a Command and Control (C2) data link.

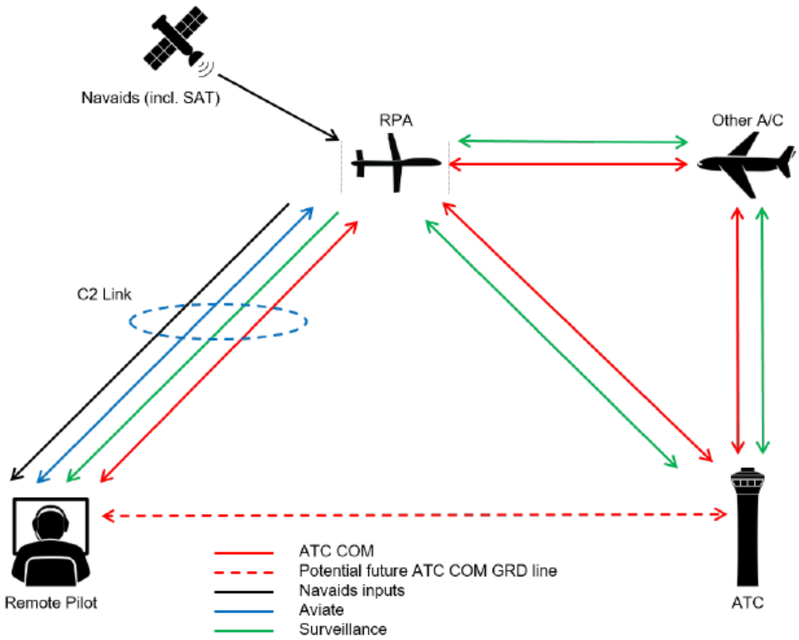


FIGURE 4.1.1-1: RPAS AND ATM SYSTEM INTERFACES

Many types of UA exist, using fixed wing, rotary wing, multirotor, tilt wing / duct / engine concepts, with different size and performance. Even if no common classification is accepted worldwide, UA are often recognised as: High Altitude and

Long Endurance (HALE), Medium Altitude and Long Endurance (MALE), Tactical UA, Small, Mini or Micro UA.

FIGURE 4.1.1-2: EXAMPLES OF HALE, MALE AND TACTICAL UA

FIGURE 4.1.1-3: EXAMPLES OF SMALL TO MICRO UA

Classification of UAS Operations is defined according to the following risk based and operation-centric approach:

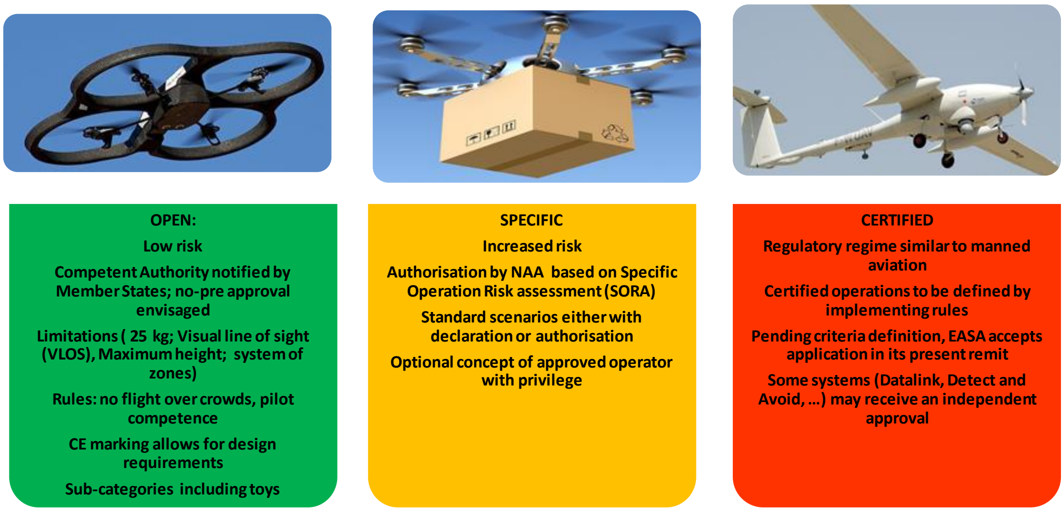


FIGURE 4.1.1-4: UAS CLASSIFICATION ACCORDING TO EASA REGULATORY FRAMEWORK[6]

---

[6] EASA Opinion No 01/2018 ‘Introduction of a regulatory framework for the operation of unmanned aircraft systems in the “open” and “specific” categories’ (RMT.0230) and Delegated Regulation (EU)

Regarding the scope of this study, UAS operating in the Specific or the Certified categories are of interest, mainly due to the relatively higher level of risks the operation over urban areas, relatively close to people or infrastructure, flying Beyond Visual Line of Sight (BVLOS) and finally transporting passengers or potentially dangerous parcels. In the environment considered for the study, we will mainly find relatively small UA, able to operate in an urban area or close to infrastructure to perform their expected mission. As an indication, such UA would be with a weight from a few kgs to a few 100s of kg, and with dimensions from a few decimetres to a few meters. When the capability to transport people (see VTOL in the next section) will be authorised, much larger and heavier aircraft will be encountered.

In the future, it is expected that UAS will have an accepted capability to operate automatically (according to defined flight plans) or autonomously (with trajectories and flight paths directly adapted at the UA level) without the need for a RP. We will then move to the notion of mission manager and / or mission supervisor, being only responsible for the safe execution of the operational mission. In this case, the supervisor might be only able to allow or interrupt safely any UA mission under his responsibility. Even if usually one UA is controlled by one RP, it is already feasible to control multiple UA from a single RPS. This capability will be further extended to move to this fleet management concept, needed to offer future UAS-based services: e.g. global surveillance or inspection, parcel delivery, air taxi….

According to the European Drones Outlook Study, typical missions for UAS were considered along different sectors of activity [16]:

1. Agriculture: Drones could help enable precision agriculture that will be critical to meet productivity needs for Europe and support greener farmer practices that are a focus of the EU Common Agricultural Policy (CAP) of 2020. The use of drones for precision agriculture creates two primary mission types:
    - long range surveying (performed mostly by fixed wing drones) to execute remote sensing at an altitude of about 500 feet over fields;
    - long range light payload drones to do precise spraying of chemicals at altitudes below 50 ft over fields.
2. Energy: Drones may reduce a variety of risks to personnel performing hazardous tasks, to the environment by properly maintaining assets and to the infrastructure overall by limiting the amount of downtime to Europe that already is a heavy importer of resources and pays higher energy prices than other regions. In the energy sector, drones are expected to improve maintenance and be used for inspections, which are segmented into two primary mission types:
    - local site inspections, performed by multicopters operating today in visual line of sight (VLOS) and below 500 feet (ft) altitude, and potentially very close to the infrastructure (a few feet);
    - long range utility inspections for which the fleet is expected to be composed of BVLOS fixed wing drones flying near 500 ft of altitude with potentially, some certified drones operating at higher altitude (likely between 1000 and 10.000 ft).
3. Public safety and security: Drones could be used by a variety of authorities to better assess and monitor hazardous situations, complete search and rescue missions, gather evidence for investigations and detect and prevent other crises. This security includes making it easier, more effective to conduct border security and maritime surveillance and extends into providing the capability to prevent and add disaster relief (e.g., forest fires, floods, earthquakes) with aerial

---

2019/945 of 12 March 2019 on "unmanned aircraft systems and on third-country operators of unmanned aircraft systems" views and monitoring. Drones also have the potential at low altitudes to assist first response teams, primarily fire and police, in identifying civilians, gathering evidence, tracking fugitives and assessing other safety hazards more immediately, as today's helicopters for such purposes as both limited in quantity and expensive in operation. Similar type of missions will be certainly considered for news and media coverage of the same situations. As an added benefit for local communities, these drones could also offer potential to conduct bridge inspections among other local needs as resources are available. These needs create three general mission types:

- stationary surveying by multicopter drones that are operated by on site forces or medias, usually carrying a drone in their vehicle. Operations will be close to the ground (below 150 ft);
- long range surveying by future versions of the technology that operate more beyond visual line of sight and are operated more centrally at altitudes near or below 150 ft;
- higher altitude (i.e., above 1500 ft) surveying drones to screen large areas as part of border security, maritime surveillance and environmental protection.

4. E-commerce and delivery: Urgent packages, including medical supplies, could be completed in a fraction of the time and online retailers could benefit from increased accessibility in both urban and remote areas:
   - Missions will be performed at altitude generally below 500 ft, with take-off and landing phases done directly at the manufacturer or retailer sites, at the customer or distributor locations, almost anywhere in urban or rural environment;
   - The concept will benefit from the capabilities offered by automatic “fleet” operations (without pilots involved).
5. Mobility and transport: The infrastructure of today, i.e., railways, may be monitored and kept secure using observation and surveillance drones. Future forms of passenger or cargo aircraft are expected to operate safely without the requirement of on-board pilots.
   - For surveillance and inspection missions, see §2 and §3;
   - For transport, see 4.1.2 on VTOL below.

4.1.2 VTOL

In recent years, many companies and start-ups have launched the development of (electric) VTOLs, that can be classified in the following categories according to the concept adopted for lift and thrust:

1. Vectored Thrust: The vectored thrust eVTOLs have a wing for an efficient cruise and use the same propulsion system for both hover and cruise.

FIGURE 4.1.2-1: VECTORED THRUST VTOL

2. Lift + Cruise: The lift + cruise eVTOLs have a wing for an efficient cruise, like vectored thrust eVTOLs, but they use two different propulsion systems for hover and cruise flight.

FIGURE 4.1.2-2: LIFT + CRUISE VTOL

3. Wingless: The wingless eVTOLs are multirotors. They have large disk actuator surface which makes them efficient in hover, but they do not have a wing for an efficient cruise. These vehicles are suited for short-range operations in cities where they can fly over traffic jams.

FIGURE 4.1.2-3: WINGLESS VTOL

4. Hoverbikes: Hoverbikes are multirotors that can be flown like a motorbike. The pilot typically sits on a saddle or is standing on a light structure. Extension of this concept can be seen in the flyboard concept.

FIGURE 4.1.2-4: HOVERBIKE VTOL AND FLYBOARD

5. eHelos: eHelos are conventional helicopters with electrical engines.

FIGURE 4.1.2-5: EHELO VTOL

Current regulation framework for VTOL is considering manned aircraft, meaning with a pilot on board [6]. However, the future market is based on the expectation that unmanned VTOL will be allowed to be used for all missions. Almost all VTOL projects are developed in that direction, thus bridging the VTOL principle to the UAS domain in a few years.

VTOL missions are directly related to the notion of UAM, as enablers for the On-Demand Mobility (ODM) concept of operations.

- Urban Air Mobility can be defined as safe and efficient air traffic operations in a metropolitan area, i.e. in the congested areas of cities, towns or settlements.
- On-Demand Mobility relates to air traffic operations between any origin and any destination, without the delays associated with scheduled service in traditional commercial aviation.

Note that according to the regulation:

- Congested area means "any area which is substantially used for residential, commercial or recreational purposes" [10],
- Aerial operations in congested areas for civil purposes are limited below certain heights, "except when necessary for take-off or landing, or except by permission from the competent authority" [9].

UAM operation is not restricted to cities as very often the mission will include a connection flight toward or from airport (controlled or not) or site outside congested areas (e.g. storage areas, industrial zones…).

Examples of UAM missions are already foreseen:

1. "air metro operation": regularly scheduled mission transporting passengers between a set of fixed locations inside cities (e.g. downtown, visitors centre, railway station…), and or outside (e.g. airport, railway station, business districts, shopping mall, hotels area, recreation centre…);
2. Air cargo: similar to air metro for regular transport of goods between any fixed location inside cities and or outside;
3. On demand air taxi: such unscheduled air traffic operations between any origin and any destination, should become the most common VTOL mission. Important safety aspects are a cleared distance to obstacles (e.g. buildings and skyscrapers) and avoiding flying above congested areas (important human gatherings). Clearly defined safety procedures should avoid lethal situations for both, passengers on board and people on the ground, in case of an emergency;
4. Security mission: another form of unscheduled air traffic operation between any origin and any destination to provide emergency medical evacuation, rescue operation and humanitarian mission;
5. Law enforcement operations;
6. News gathering;
7. Weather monitoring;
8. Ground traffic assessment.

The profile of a typical VTOL mission includes three main parts:

- A vertical take-off from a so called Vertiport, eventually followed by a transition phase to the normal flight configuration, and a climb to operating altitude;
- Thereafter follows a cruise flight, most probably over an urban area;
- At the destination, the aircraft will descent and approach the port vertically until touching down.

While missions 1 and 2 will clearly use regular and usually pre-planned routes, eventually adapted for the mission according to the constraints of air traffic and city events, the other types of missions will use on-the-spot defined routes. The cruise phase is due to be flown at medium height (e.g. above 500 ft), with potentially lower height (e.g. below 150 ft) for e.g. short distance taxi, on-demand missions, rescue or surveillance mission, etc.

Missions 4 to 8 will also include phase(s) where the VTOL will overflight dedicated areas to perform its operational mission: observation, surveillance, coverage of events, support to rescue missions… According to the mission and the payload used (sensors, observers, sling…), such operational phases could require a low altitude flight (less than 150 ft) with part of trajectory between (and very close from) urban infrastructure.

VTOLs are expected to operate from “Vertiports”. In addition to the existing airport infrastructure, it has been proposed that the repurposed tops of parking garages, existing helipads, and even unused land surrounding highway interchanges could form the basis of an extensive, distributed network of vertiports (VTOL hubs with multiple take-off and landing pads, as well as charging infrastructure) or single-aircraft “vertistops” (a single VTOL pad with minimal infrastructure).

Some concepts even introduce the use of any flat area with enough clearance from obstacles, urban infrastructure and risk to population for single-aircraft VTOL operation: e.g. empty parking lot, public garden, etc. Not to mention more advanced concepts considering much closer operations ….

.

4.2 GENERAL CHARACTERISTICS OF NEW URBAN AREA OPERATIONS

This intend of this section is to provide a synthesis of the new urban operations in order to have a good appraisal of the minimum distance that could separate the new vehicle from any HIRF sources.

This synthesis will be used to identify the potential HIRF levels that could affect the vehicle during its urban operations.

TABLE 4.2 provides a summary of the operation types that could specifically be encountered with these new vehicles, indicating different notions of proximity to ground and urban infrastructure.

TABLE 4.2: MINIMUM DISTANCES TO URBAN INFRASTRUCTURE

Use case	Height	Proximity[7]	Comment
Rural 1	Less than 500 ft	More than 25 m	Low level survey or line inspection mission
Rural 2	Less than 50 ft	Less than 10 m	Very low level crop spraying mission
Urban 1	Less than 500 ft	Less than 25 m	UAM mission over cities, or between city and airport/delivery site
Urban 2	Less than 150 ft	Less than 10 m	UAM mission close to buildings (in “urban canyons”) or local inspection mission
Vertiport 1	Less than 50 ft	More than 25 m	Operations at heliport or equivalent protected areas
Vertiport 2	Less than 50 ft	Less than 10 m	Operations at city vertiport or on top of buildings

4.3 SPECIFIC HIRF ENVIRONMENT FOR NEW OPERATION WITHIN URBAN AREA

This section provided the main characteristics of the HIRF environment that should be considered for new operations in urban areas.

The following principles were applied to define such new environment:

- Due to the high density of population within such area, high power transmitters have not to be considered (i.e. they are located outside city).
- All transmitters implemented in urban areas are subject to power limitation to protect human being, this is true for radio broadcast transmitters (i.e. FM broadcast) and even for TV broadcast transmitters. A few medium power TV broadcast transmitters could be found in the peripheral area of cities.
- Mobile telephony transmitters implemented in urban areas will mainly use medium size or local area antenna systems, as described in section 3.2.2. Only a few sites could be fitted with large coverage antenna system.

Therefore, the main element that could drive the need for a more stringent HIRF environment will be the minimal separation distance between the new flying vehicle and the transmitter itself.

It is assumed that this minimal distance will be primarily defined to protect the population and the urban construction and equipment. The following assessment in section 4.4 considers several cases of transmitters to be found in the urban areas and defines the HIRF levels that should be necessary versus distance to transmitters.

[7] Proximity is indicated in this table as the horizontal distance from infrastructure.

TABLE 4.2 will be used in a second step in correlation with the minimal separation distance that could be expected for urban operation as defined in section 4.2.

To complete this picture, a specific case has also been addressed in response to the typical urban environment regarding mobile telephony. This case considers the following scenario: urban operation in the close vicinity of a 5G base station including the potential cumulative additional effect of the other base stations in the vicinity and the contribution of mobile smartphones or phones in the vicinity. This analysis is presented in section 4.3.2.

4.3.1 HIRF existing environment applicability

The urban environment can be compared to the following elements of the three HIRF environments.

TABLE 4.3.1: URBAN ENVIRONMENT CHARACTERISTICS AND HIRF APPLICABILITY

Case	Point 1	Point 2	Specificities of flight domain	Ways to mitigate HIRF ENV	Environment
1	Heliport near Airport	City Building Heliport	Distance observed with antennas on building Airport proximity Distance	Heliport location, if possible far from Airport radars – end of runway. No consideration of aircraft in vicinity	Normal environment reduced in radar frequency range. Possibly increased to covers antenna proximity on building and new services (3G/4G/4G)
2	City Heliport (City 1)	City Heliport (City 1)	Distance observed with antennas on building	Severity reduced to actual Heliport ENV	Pure urban HIRF environment, drastically limited for Hazards of Electromagnetic Radiation to Personnel (HERP) purpose. 4G/5G and directional satellites antennas (X, Ka, Ku)
3	City Heliport (City 1)	City Heliport (City 2)	Distance observed with antennas on building Full field area emitters with flight altitude similar to rotorcraft (500feets) considered in HIRF ENV III.	Rotorcraft severe ENV should be avoided with preserving exclusion areas and so defining specific path in order to limit at ENV required to cover 1. Band-drivers considered in HIRF environment III are not present in urban flight domain.	

4.3.2 Multi transmitters threat analysis

This section is addressing the potential mechanism that could result from an environment with multiple radiated sources that we have defined as the aggregated mode. To address this potential mechanism the 5G mobile phone infrastructure was considered.

This part of the study was conducted by EMC RASECK. The full report of their analysis is provided in Annex 5.

As a summary, the analysis starts with a scenario in which the hostile radio environment is composed of a main base station (very close from the victim avionic or aircraft system) and of several adjacent base stations within a 25 km area. In addition to the ground fixed infrastructure, multiple mobile phones were also considered in the vicinity of the victim avionics or aircraft system. Indeed, the scenario considered the victim at different slant range from the main Base station (i.e. 25 and 10 meters).

The assessment applies a two steps approach:

- A first step considers that all contributions are summed together arithmetically. This simulation provides a higher limit of this potential threat.
- A second step considers the effect of the phase of the individual contributions leading to a more realistic vectoral summation of all the contributors. When applying this more realistic principle, the additional contribution on top of the main base station contribution is rather small.

The results of the first step are summarised as follows:

- 263 V/m for dense urban environment, due to base stations
- 116 V/m for rural environments, due to base stations
- 94 kV/m, for dense urban environments due to user equipment (air vehicle altitude: 1.5 m)
- 385 kV/m, for dense urban environments due to user equipment (air vehicle altitude: 25 m)

It must be emphasized that this very simple adding approach is not actually correct and the values, especially for the user equipment scenarios which consider a high density of mobile phone user in the urban environment (up to 10^6 mobile phones / km^2), are not meaningful. A physically more realistic approach makes use of the assumption that the aggregated electrical fields are not strictly monochromatic (i.e. phase variable) and hence only a vector approach for the summation is appropriate. This was the step 2 of the simulation. The results are as follows:

- 62 V/m for dense urban environment, due to base stations
- 109 V/m for rural environments, due to base stations
- 25 V/m, for dense urban environments due to user equipment (air vehicle altitude: 1.5 m)
- 18 V/m, for dense urban environments due to user equipment (air vehicle altitude: 25 m)

As a conclusion, it is clearly established that the field aggregated mechanism is not an additional threat that needs to be addressed specifically. Therefore, regarding the mobile phone (5G was used here but the assessment of any of the previous technologies will give the same results), the only case to consider is the proximity of the wide coverage base station. In the results of the second step simulation, even this case is widely below the HIRF value in the relevant frequency band (i.e. 160 to 400 V/m for the various HIRF environments).

4.4 URBAN HIRF ENVIRONMENT ANALYSIS

4.4.1 Generalities

The assessment of HIRF environment generated by typical services present in urban and peri-urban areas, such as GSM, TV, HF and FM radio broadcasting, relies on:

- Far field assumption
- Typical power of emitter (Pe) and gain (G)

The electrical field E resulting of these emitters is computed following the expression at the distance d:

$$E(d) = \sqrt{(Pe*G*30)}/d$$

To facilitate the understanding of the assessment, a trade-off between separation distance and HIRF hardening is provided in a table for each service. The minimum distance to cope with the proposed HIRF environment for urban operation is **written in green** in the tables.

4.4.2 GSM service

For GSM service, 3G/4G and 5G are considered with typical power and gain of most powerful emitters located in urban and peri-urban areas, i.e. long-range antennas (P=80W, G=50) which are installed for example on building roof or at the tip of mast. For medium and short rage antennas, the powers are lower (respectively <6.3W and <0.25W) and then are not considered in this study [1].

TABLE 4.4.2: ELECTRIC FIELD FROM GSM SERVICE

GSM Service	Frequency Band (MHz)	Power considered (W)	Gain (dB)	E @ 5m **V/m**	E @ 10m **V/m**	E @ 20m **V/m**	E @ 50m **V/m**
4G 700	**703-788**	**80**	**17**				
3G 900	**876-959**	**80**	**17**				
3G 2100	**1920-2170**	**80**	**17**				
4G 800	**791-862**	**80**	**17**				
4G 1800	**1710-1880**	**80**	**17**				
4G 2600	**2500-2690**	**80**	**17**				
5G	**3400-3800**	**80**	**17**				
5G	**26000**	**80**	**17**	**<70V**	**<<35V**	**<<17V**	**<<7V**

Clearances rules are already respected for the most powerful emitters for human health purpose (between 5 and 15m in antenna axis) in order to be compliant with HERP regulation.

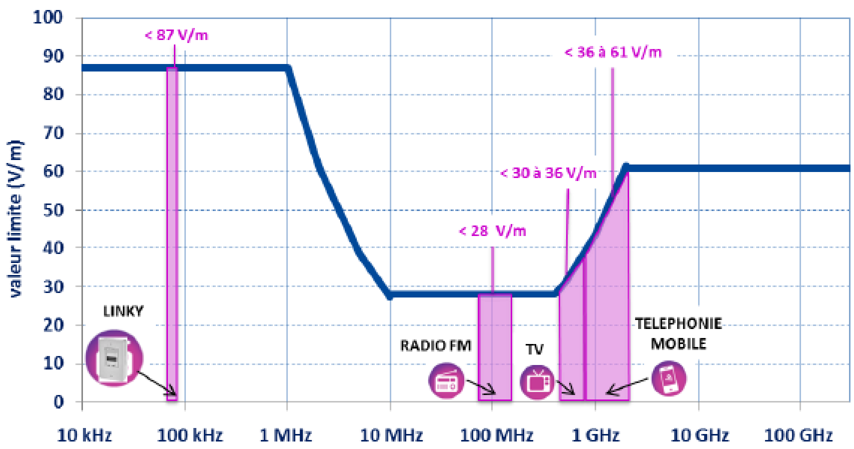


FIGURE 4.4.2: EXAMPLE OF HERP LIMITATION

At 10m from GSM emitters, the electric field remains below 35V/m. If the clearance distance regarding flight near urban buildings is at least 10m, a minimum hardening at

50V/m on GSM related frequency ranges would provide a significant margin while avoiding operational constraints for a specific HIRF purpose.

4.4.3 TV broadcasting service

For TV service, Terrestrial Digital TV is considered with a typical power of emitters far from cities as worst case. The assumptions are based on Limeux site [18] with 80kW antenna (pylon height around 150-200m).

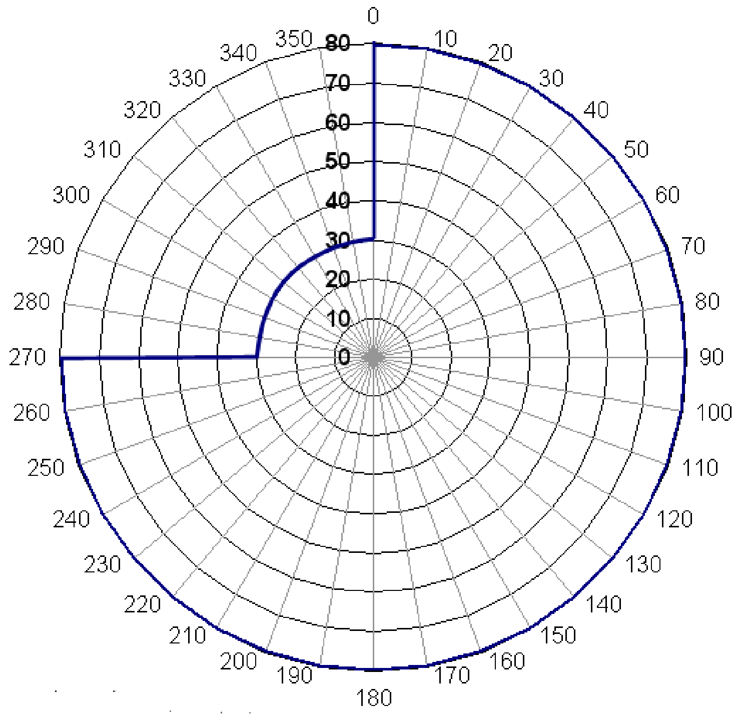


FIGURE 4.4.3: TYPICAL RADIATION PATTERN OF LIMEUX EMITTERS

TABLE 4.4.3: ELECTRIC FIELD FROM TV BROACAST SERVICE

TV service	Frequency Band (MHz)	Power considered (KW)	Gain	E @ 5m V/m	E @ 10m V/m	E @ 20m V/m	E @ 50m V/m
Limeux emitter example	470-790 MHZ	80	1	<310	<155	<78	<31V

The minimum protection proposed at 50V/m on GSM related frequency ranges would be also relevant for TV frequency because covering with margin:

- flight at 150 ft (50m) from the typical most powerful antennas far from cities, i.e. up to 80 kW considering as a worst case the VTOL in the maximum emission angle,
- flight at more than 10m from emitters in urban/suburban while power is less than 3 kW what should covers actual antennas.

This strategy would lead to a reasonable protection because Terrestrial Digital TV relay antennas in urban environment are much less powerful than the worst case considered for the above electric field computation. The proposal can be refined according clearance distance and worst-case power, or antennas located in urban environment.

The 174 MHz-230 MHz frequency range was used for analogic TV. This range has been reallocated to numeric radio (DAB) or numeric TV (DVB-T) as function of country. The same logic of protection may be applied in this frequency range with a 50/m level.

4.4.4 FM broadcasting service

For FM radio broadcasting, assumptions are considered with typical power of emitters far from cities as worst case. The assumptions are based on Limeux site [18] with up to 5 KW antennas.

TABLE 4.4.4: ELECTRIC FIELD FROM FM RADIO BROADCASTING SERVICE

FM radio broadcasting	Frequency Band (MHz)	Power considered (W)	Gain	E @ 5m V/m	E @ 10m V/m	E @ 20m V/m	E @ 50m V/m
Example of Limeux	**87.5-108 MHz**	Max =5000	1	<80	<40	<20	<8

At 10m of such worst-case emitters in urban or peri-urban environment, the electric field remains below 40V/m for a worst-case antenna. A 50V/m protection would be sufficient if a minimum of 10m clearance distance is confirmed.

4.4.5 HF broadcasting and amateur radio emissions

Even if not present in urban environment and only in cases of the suburban area of some cities (often the capital of the country), the presence of some HF high-power antennas shall be considered.

TABLE 4.4.5: ELECTRIC FIELD FROM HF RADIO BROADCASTING SERVICE

HF radio broadcasting	Frequency Band (MHz)	Power considered (KW)	Gain	E @ 5m V/m	E @ 10m V/m	E @ 50m V/m	E @ 100m V/m
Worst Case	2-30 MHz	500	1	<775	<387	<78	<38

These HF broadcasting antennas generate a significant electric field (around 400V/m at 10m) and, considering that 50V/m would be a limit on VTOL design (frequency band recognized as a design driver, especially for the shielding of cabling), an exclusion area around these emitters according the actual power emitter is the recommended way to manage these quite rare emitters. A clearance distance of 100m around the antenna will typically be required.

The operational constraint should be limited due to the decrease of this type of installations.

Regarding the Amateur Radio emissions, a 50V/m protection covers the Amateur Radio antennas located in urban area up to 5KW with a separation distance of 10m.

4.4.6 Other transmitting systems

As explained in 2.3 and based on a recent HIRF study performed by aircraft manufacturers, equipment suppliers and test laboratory [17], it has been evidenced that electronic equipment becomes less sensitive to electromagnetic field above 6GHz. Then, if an electronic equipment does not present any upset when aggressed with a certain pulse and average mode levels up to 6GHz, the equipment should withstand at least these levels above 6 GHz except for equipment circuit operating at frequency above 6GHz.

Moreover, even the less severe environment of the present applicable HIRF regulation requires a significant protection below 6GHz, i.e. 3000V/m in pulse mode and 120-160V/m in average from 2GHz up to 6GHz with normal HIRF environment). Then the applicable HIRF environments provide a significant HIRF protection for upper frequency ranges and therefore against emitters which are commonly used in X, Ka and Ku bands in urban area.

Consequently, no further analysis will be performed in this preliminary study regarding these frequency bands because a minor risk is identified to be not covered with present HIRF environments."

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 HIRF REQUIREMENT APPLICABILITY FOR CONVENTIONAL AIRCRAFT AND ROTORCRAFT

The analysis about the evolution of existing services in 3.2.1 evidenced that the present HIRF environment remains relevant for the certification of conventional fixed-wing Aircrafts and Rotorcrafts because of the global reduction of emitter power in reason of:

- technology evolutions, e.g. increasingly use of solid state radars,
- service evolutions, e.g. terrestrial analogic to numeric television,
- progressive disappearance of some services, e.g. HF radio broadcasting,
- growing awareness of HERP and relative regulation.

Nevertheless, the radar technology evolution (solid-state) leads to longer pulse duration even if peak powers are significantly reduced compared to former valve-based technology. This evolution should be considered in ED-14G/DO-160G section 20 [8] with longer pulse duration for equipment qualification tests against HIRF. Indeed, some electronics design may be more sensitive to these longer pulse durations.

An opportunity to relax HIRF environment in the coming years has been identified in 2-100MHz frequency range and especially in 30-100MHz band because:

- this last band inherits of 2-30MHz protection level historically identified and not to a specific need in this band,
- the impact of this required level leads to a significant HIRF protection, especially for Rotorcrafts.

RECOMMENDATION 1:

The levels of the HIRF environments defined in the regulation should be maintained without modification for the certification of conventional Aircraft and Rotorcrafts.

5.2 HIRF requirements to be applied on UAS and VTOL operating in cities

Considering future VTOL missions as presented in chapter 4, both airports and, urban and suburban environments shall be considered. Indeed a typical mission is the transport of Very Important Persons (VIPs) from a Heliport station accessible by airport passengers up to a suburban place (e.g. stadium) or a business building roof.

Then the HIRF normal environment of the present regulation established to be representative of the airport HIRF environment shall be considered as a basis of the VTOL HIRF hardening.

However, the band-driver emitters leading historically to most severe environments (certification and rotorcraft severe) should not be considered for the establishment of VTOL HIRF threat envelope for operation in urban and suburban areas because:

- Not relevant since most of these band-driver emitters are far from the cities. For most of services only the receivers are located in the urban area.
- New service like GSM is intensively deployed in urban area through a dense network of low-power antennas (<80W) that minimize electric field strength.
- Would lead to a significant HIRF protection effort at VTOL level, i.e. regarding the electronic equipment design and VTOL structure and cabling faradizations.

In the unlikely situation of the presence of this kind of very powerful emitters near cities, e.g. as some HF and Terrestrial Digital TV broadcasting emitters with power higher than 5KW, it is recommended to manage the safety using a flight exclusion area around the emitter in order to limit the VTOL exposure to the level the VTOL is able to withstand. This exclusion mechanism is already used in classic aviation to forbid the entry in dangerous areas or military zones.

Then a reduced protection can be considered in the related frequency ranges as preconized in 4.4 with the application of a 50V/m requirement what represent a reasonable compromise.

This compromise should not definitively lead to prejudicial flight limitation because of the growing reduction of these high-power emitters around cities.

RECOMMENDATION 2:

The rare presence of High Power emitters in urban/suburban area should be managed by defining around these emitters a flight exclusion area, i.e. emitters with a power higher than 5KW

Regarding the specificity of the VTOL missions in urban/suburban area, both the characteristics of the emitters deployed in this new flight domain and the potential significant proximity with VTOL have been considered. At this end, an analysis has been performed in section 4.4 to assess the electric field at different distances of worst-case emitters dedicated to GSM, TV and radio broadcasting services.

With the assumption that a minimal clearance distance of 10 m from urban infrastructure would be reasonable for flight safety purpose beyond any electromagnetic consideration, the electric field estimations near the typical antennas present in urban and suburban environment lead to increase normal environment levels up to 50V/m in the related frequency ranges with this separation distance. This level would limit the effort regarding the HIRF protection at VTOL level while avoiding exclusion areas in the vicinity of frequent emitters which may be encountered in urban area.

Nevertheless, this recommended level can be tailored according separation distance rules defined in coming months and years.

It shall be especially noticed that if the operational safety clearance distances to be applied for population protection within city building and on ground is higher than the 10 m assumption considered in this preliminary study, the proposed protection could be mitigated.

As the result, the recommendation is to develop an *ad hoc* tailored new HIRF environment based upon the normal HIRF environment, to cover the new urban operations. This new HIRF environment is presented in the following TABLE 5.

RECOMMENDATION 3:

The level of protection on the overall [2MHz-1GHz] frequency range should be defined at 50V/m in the purpose to cover new VTOL mission profiles in urban area. This recommendation leads to a new UAS/VTOL HIRF environment based on normal environment, modified by applying the evolution written in green (relaxation) and red (increase) in the TABLE 5.

TABLE 5: UAS AND VTOL ENVIRONMENT PROPOSAL ON THE BASIS OF NORMAL HIRF ENV

FREQUENCY	FIELD STRENGTH (V/m)		Tailoring logic
	PEAK	AVERAGE	
10 kHz - 100 kHz	20	20	
100 kHz - 500 kHz	20	20	see way forward
500 kHz - 2 MHz	30	30	see way forward
2 MHz - 30 MHz	100=>50	100=>50	Reduction of constraint to limit impact on VTOL design– possibly using exclusion area
30 MHz - 70 MHz	10=>50	10=>50	Hardening consistent with adjacent band- Then no significant impact on HIRF VTOL protection
70 MHz - 100 MHz	10=>50	10=>50	Hardening for FM broadcasting
100 MHz - 200 MHz	30=>50	10=>50	Hardening for FM broadcasting
200 MHz - 400 MHz	10=>50	10=>50	Hardening for TV
400 MHz - 700 MHz	700	40=>50	Hardening for GSM &TV TNT
700 MHz - 1 GHz	700	40=>50	Hardening for GSM
1 GHz - 2 GHz	1300	160	
2 GHz - 4 GHz	3000	120	
4 GHz - 6 GHz	3000	160	
6 GHz - 8 GHz	400	170	
8 GHz - 12 GHz	1230	230	
12 GHz - 18 GHz	730	190	
18 GHz - 40 GHz	600	150	

For the UAS and VTOL possibly dedicated to missions outside the urban/suburban perimeter, the present regulation should remain relevant for the HIRF protection.

ANNEX 1: REFERENCES INDEX

[1] ANFR, "Rapport technique sur les déploiements pilotes de petites antennes en France", December 2018

[2] Bull, D A, ERA Technology, Inc., ERA Report 98-0816, Development of the HIRF Environment, October 1998.

[3] CEPT ECC report 066 "Protection of aircraft from Satellite Earth Stations operating on the ground in the vicinity of airfields" June 2005 (now superseded by ECC Report 272, 26 January 2018) https://www.ecodocdb.dk/download/54d08c59-fc4d/ECCRep066.pdf

[4] EASA CS-23/25/27/29, interim HIRF policies and Certification Review Items (CRIs).

[5] EASA AMC 20-158, 'Aircraft Electrical and electronic system high intensity radiated fields (HIRF) protection", 2015.

[6] EASA "Special Condition for small-category VTOL aircraft" - Issue of 1 July 2019

[7] EUROCAE ED-107A / SAE ARP5583, "Guide to certification of aircrafts in a Hight-Intensity Radiated Field (HIRF) Environnement", July 2010.

[8] EUROCAE ED-14G/RTCA DO-160G standard, *"Environmental conditions and test procedures for airborne equipment",* May 2011.

[9] European Commission Implementing Regulation (EU) No 923/2012 of 26 September 2012 laying down the common rules of the air and operational provisions regarding services and procedures in air navigation and amending Implementing Regulation (EU) No 1035/2011 and Regulations (EC) No 1265/2007, (EC) No 1794/2006, (EC) No 730/2006, (EC) No 1033/2006 and (EU) No 255/2010 (i.e. SERA.3105 and SERA.5005(f))

[10] European Commission Regulation (EU) No 965/2012 of 5 October 2012 laying down technical requirements and administrative procedures related to air operations pursuant to Regulation (EC) No 216/2008 of the European Parliament and of the Council

[11] FAA, U.S. Title 14, Code of Federal Regulations (14 CFR) 23.1308, 25.1317, 27.1317, 29.1317, and applicable HIRF Special Conditions.

[12] FAA, AC 20-158A, ''The Certification of Aircraft Electrical and Electronic Systems for Operation in the High-intensity Radiated Fields (HIRF) Environment'', May 2014.

[13] International Telecommunication Union, Radio Regulations, 2016. https://www.itu.int/pub/R-REG-RR-2016

[14] NASA-RP-1374, Electronic Systems failures and anomalies attributed to electromagnetic interference, July 1995

[15] Naval Air Warfare Center Aircraft Division (NAWCAD) Technical Memorandum, Report No. NAWCADPAX-98-156-TM, High-intensity Radiated Field External Environments for Civil Aircraft Operating in the United States of America (Unclassified), dated November 12, 1998. A copy of the NAWCAD Technical Memorandum. http://www.tc.faa.gov/its/worldpac/techrpt/ar98-69.pdf

[16] SESAR European Drones Outlook Study "Unlocking the value for Europe" – Nov. 2016

[17] Therond, Frederic et al., "A refresh on HIRF Equipment susceptibility above 8GHz". EMC Europe, Barcelona, 2019.

[18] Wikipedia, Émetteurs de Limeux, consulted 2 December 2019. https://fr.wikipedia.org/wiki/%C3%89metteurs_de_Limeux

ANNEX 2: AMC20.158 - HIRF environments

TABLE A.2-1: CERTIFICATION HIRF ENVIRONMENT

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz - 100 kHz	50	50
100 kHz - 500 kHz	50	50
500 kHz - 2 MHz	50	50
2 MHz - 30 MHz	100	100
30 MHz - 70 MHz	50	50
70 MHz - 100 MHz	50	50
100 MHz - 200 MHz	100	100
200 MHz - 400 MHz	100	100
400 MHz - 700 MHz	700	50
700 MHz - 1 GHz	700	100
1 GHz - 2 GHz	2000	200
2 GHz - 4 GHz	3000	200
4 GHz - 6 GHz	3000	200
6 GHz - 8 GHz	1000	200
8 GHz - 12 GHz	3000	300
12 GHz - 18 GHz	2000	200
18 GHz - 40 GHz	600	200

TABLE A.2-2: NORMAL HIRF ENVIRONMENT

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz - 100 kHz	20	20
100 kHz - 500 kHz	20	20
500 kHz - 2 MHz	30	30
2 MHz - 30 MHz	100	100
30 MHz - 70 MHz	10	10
70 MHz - 100 MHz	10	10
100 MHz - 200 MHz	30	10
200 MHz - 400 MHz	10	10
400 MHz - 700 MHz	700	40
700 MHz - 1 GHz	700	40
1 GHz - 2 GHz	1300	160
2 GHz - 4 GHz	3000	120
4 GHz - 6 GHz	3000	160
6 GHz - 8 GHz	400	170
8 GHz - 12 GHz	1230	230
12 GHz - 18 GHz	730	190
18 GHz - 40 GHz	600	150

TABLE A.2-3: ROTORCRAFT SEVERE HIRF ENVIRONMENT

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz - 100 kHz	150	150
100 kHz - 500 kHz	200	200
500 kHz - 2 MHz	200	200
2 MHz - 30 MHz	200	200
30 MHz - 70 MHz	200	200
70 MHz - 100 MHz	200	200
100 MHz - 200 MHz	200	200
200 MHz - 400 MHz	200	200
400 MHz - 700 MHz	730	200
700 MHz - 1 GHz	1400	240
1 GHz - 2 GHz	5000	250
2 GHz - 4 GHz	6000	490
4 GHz - 6 GHz	7200	400
6 GHz - 8 GHz	1100	170
8 GHz - 12 GHz	5000	330
12 GHz - 18 GHz	2000	330
18 GHz - 40 GHz	1000	420

ANNEX 3: LIST OF EXISTING SERVICES (NON EXHAUSTIVE) USED BY THE INTERNATIONAL TELECOMMUNICATION UNION (ITU)

TABLE A.3: NON-EXHAUSTIVE ITU SERVICES LIST

Ground services	Airside services	Satellite based services
Fixed service Broadcasting service Radio-location service Radio-determination service Aeronautical radio-navigation service Maritime radionavigation service Radio-navigation service Industrial, Scientific and Medical (ISM) applications service Meteorological aids service Port operations service Ship movement service Coordinated Universal Time (UTC) service Amateur service Radio direction-finding service Radio astronomy service Standard frequency and time signal service	Aeronautical mobile (R)service Aeronautical mobile (OR) service Maritime mobile service Land mobile service	Aeronautical mobile satellite (R) service Aeronautical mobile satellite (OR) service Aeronautical radio-navigation satellite service Mobile satellite service Fixed satellite service Land mobile satellite service Maritime mobile satellite service Broadcasting satellite service Inter-satellite service Space operation Radio-determination satellite service Earth exploration satellite service Meteorological satellite service Standard frequency and time signal satellite service Amateur satellite service Radionavigation satellite service Maritime radionavigation satellite service Radiolocation satellite service

ANNEX 4: ACRONYMS

2G-5G:	Second to Fifth-generation (of mobile telecommunications technology)
ABS:	Antiblock Braking Systems
AM:	Amplitude Modulation radio signal
AMC:	Acceptable Means of Compliance
ANFR:	Agence nationale des fréquences (French radio regulator)
AP:	Digital Application Protocol
BCI:	Bulk Current Injection
BVLOS:	Beyond Visual Line of Sight
C2/C3:	Class 2 (under 4kg) and Class 3 (under 25kg) for UAS
C2:	Command and Control (Data link for UAS)
CEPT:	European Conference of Postal and Telecommunications Administrations
COTS:	Commercial-Off-The-shelf (equipment)
CRI:	Certification Review Item
CS:	Certification Specification
CS-29:	Certification Specification large rotorcraft
DAB:	Digital Audio Broadcasting
dB:	Decibel
DME:	Distance Measuring Equipment
DVB-T:	Digital Video Broadcasting — Terrestrial
EASA:	European Union Aviation Safety Agency
ECC:	Electronic Communications Committee (of CEPT)
EM:	Electromagnetic
FAA:	Federal Aviation Administration
FADEC:	Full Authority Digital Engine Control
FAR 29:	Federal Aviation Regulations 29 (amendment 49)
ft:	feet
FM:	Frequency Modulation radio signal
GES:	Ground Earth Station
GHz:	Giga Hertz
GSM:	Global System for Mobile
HALE:	High Altitude and Long Endurance (UAS)
HERP:	Hazards of Electromagnetic Radiation to Personnel
HF:	High Frequency
HIRF:	High Intensity Radiated Fields
ICAO:	The International Civil Aviation Organization
IFR:	Instrument Flight Rules
ILS:	Instrument landing system
ISM:	Industrial, Scientific and Medical applications service (ITU)
ITU:	International Telecommunication Union

kHz:	Kilohertz
kV/m:	Kilovolt per meter
MALE:	Medium Altitude and Long Endurance (UAS)
MHz:	Megahertz
MF:	Medium Frequency
MFD:	Multi-Function Display (in Cockpit)
ODM:	On-Demand Mobility
OFDM:	Orthogonal Frequency-Division Multiplexing
PCB:	Printed Circuit Board
RADAR:	RAdio Detection And Ranging
RF:	Radio Frequency
RP:	Remote Pilot
RPAS:	Remotely Piloted Aircraft System
RPS:	Remote Pilot Station
SAE:	Society of Automotive Engineering
SAR:	Specific Absorption Rate
SC:	Special conditions
SG:	Sub Group (EUROCAE: SG-4 of WG-112)
TACAN:	Tactical Air Navigation beacon
TV:	Television
UA:	Unmanned Aircraft
UAM:	Urban Air Mobility
UAS:	Unmanned Aircraft Systems
UHF:	Ultra High Frequency
VFR:	Visual Flight Rules
VHF:	Very High Frequency
VIP:	Very Important Person
V/m:	Volt per meter
VLOS	Visual Line of Sight
VOA:	Voice of America (transmitter)
VOR:	VHF Omni-Directional Range
VTOL:	Vertical Take-Off and Landing platforms
W:	Watt
WG:	Working Group (of EUROCAE: SG-4 of WG-112)

ANNEX 5: HIRF - AGGREGATED MODE ASSESSMENT ANALYSIS FOR NEW RADIO-COMMUNICATIONTECHNOLOGIES (EMCC)

ENGINEERING REPORT
EMCC-190103A, 2019-12-20

Title:	**HIRF - Aggregated Mode Assessment Analysis for New Radio-Communication Technologies**
Issue	2
Customer:	EuroCAE
Project:	HIRF - Aggregated Mode Assessment Analysis for New Radio-Communication Technologies

Prepared by:	Verified:
Dr. Thorsten Tischler	Dr. Martin Gabrišák

CONTENTS Page

1 Abbreviations

1-4G	Generations of Mobile Communication Standards
5G	Fifth Generation (of Mobile Communication Standards)
BS	Base station (used for mobile communication)
em	Electromagnetic
e-MBB	Enhanced-Mobile Broad Band
ETF	Entire Field Strength (sum of IFS and TAAF)
EMI	Electromagnetic Interference
EME	Electromagnetic Environment
HIRF	High Intensity Radiated Fields
IFS	Initial Field Strength (field strength in near vicinity of transmitter)
ISD	Inter-Site Distance (distance between to neighbouring stations used for mobile communication)
LOS	Line of Sight
NA	Network Architecture Approach
NBS, NUE	Number of Base Stations or User Equipments (up to the radio horizon)
ST	Statistical Approach
TAAF	Total Amount of Additional Field (due to neighbouring transmitter of a central transmitter)
PLM	Path Loss Model
UE	User Equipment
VA	Vector Accumulation Approach
VTOL	Vertical Take-off and Landing

2 Radiated field environment due to new communication technologies

2.1 Communication Technology – Introduction

Motivation for this study is the foreseeable increased field accumulation in several frequency bands due to the fifth generation (5G) of mobile communication standards. A short summary of mobile generation standards and their main characteristics is listed her [Wikipedia]:

- 1G, introduced ~1980. Analog encoding. Voice only.
- 2G, introduced ~1995. Digital encoding (e.g. GSM). Voice and Text.
- 3G, introduced ~2001. Digital encoding (e.g. UMTS). Voice, Text and Internet.
- 4G, introduced ~2009. Digital encoding (e.g. LTE). Voice, Text and
  High Speed Internet (allowing e.g. Multimedia Applications).
- 5G, introduced ~2018. Digital encoding (e.g. 5G NR). Voice, Text and
  Very High Speed Internet and/or Low Latency Internet.

Some special features of the newly introduced 5G mobile communication are [8]:

- Very High Speed Data Rates
- Low latency
- High Mobility (up to 500 km/h)
- Extremely high connection density (up to 10^6 devices / km^2)

Certain newer applications will make use of these features. ITU-R has identified 3 main scenarios:

- Enhanced Mobile Broadband, e.g. UHD video stream
- Ultra-reliable and low latency communications, e.g. autonomous car driving.
- Massive machine type communications e.g. machine to machine communication or Internet of Things (IoT).

The new features and services introduced with 5G telecommunication will increase the amount of wireless transmitted data significantly. This is managed by making use of several frequencies in the entire regime from 450 MHz (UHF) to 60 (100) GHz (EHF). Especially mobile communication systems operating in the higher frequencies will require a high density of base stations, because the attenuation due to several obstacles is typically increasing with the frequency.

2.2 Aircraft HIRF Scenario - Introduction

Based on the actual technical trends a scenario is assumed where small size air vehicles (air taxi) are operated in dense urban environments. These new air vehicles, as well as traditional larger air vehicles, will met an electromagnetic environment that is governed not only by the well-known “classical” HIRF environments as described with EuroCAE ED-107A [1], but additionally a high density of base stations and user equipment being used for wireless communication. While the classical man made HIRF environment is typically characterized and caused by standalone individual high power radar stations and radio transmitters, the hereby investigated new threats due to 5G telecommunication is characterized by massive accumulation of medium power base stations (P_{Tx} ~30 W) and low power user equipments (P_{Tx} ~ 0.1 … 0.2 W).

In order to define a point of reference for the following field accumulation calculations, it is assumed that the EMI victim (air vehicle) is next to one transmitter emitting an initial field strength (IFS) and moreover will also suffer accumulated fields from neighbouring transmitters. The distance of these additional transmitters with respect to the culprit and the nearby station is given with the different environments as defined by [6]. The Basis for the initial field strength (IFS) quantity is as follows. In order to comply with world health organisation requirements for general public exposure given with [9], maximum field strength of 61 V/m is allowed for frequencies > 2 GHz. For the lower frequency range of interest (450 MHz – 2 GHz) the value is less (28 V/m … 61 V/m). In certain EU countries e.g. Belgium or Poland the restriction are even more stringent, see [10]. In order to preserve acceptance of 5G technology accompanied by numerous base stations it is pretty likely that these field strength quantity will not be exceeded, even in vicinity of base stations. It's also a meaningful assumption related to the typical transmit power such stations apply. According to [6] the total transmit power P_{Tx} (i.e. the power including antenna gain) for base stations in different environments and user equipment is given by

- 44 dBm (25 W) for dense urban environment
- 49 dBm (80 W) for rural environment
- 23 dBm (200 mW) for user equipment scenario

Applying the formula [2]

$$E = \frac{\sqrt{30 \cdot P_{Tx}}}{r} \qquad (1)$$

one finds that the resulting field strength in r = 1 m distance from the transmitter is equals to

- 27.3 V/m for dense urban environment
- 49 V/m for rural environment
- 2.5 V/m for user equipment scenario

In order to add some safety margin this study defines the field strength in dense urban scenarios to be 61 V/m (ICNIRP public exposure limit). From this starting point the rural maximum field strength is defined to be 5 dB higher (108.5 V/m) and for the user equipment ~ 26 dB less (3 V/m) values are pretended. The fact that rural initial field strength is clearly exceeding the public exposure limit is due to the fact that in this scenario the antenna height is given by 35 m, which is out of reach for pedestrians, nevertheless air vehicles might approach closer.

2.3 Basics of typical network layout

A typical network layout for mobile communication is given e.g. by [6]. For the identified critical use case where an air taxi is operated in a dense urban environment a typical base station network will be arranged by means of hexagon shaped cells. This principle layout was used for given mobile communication standards e.g. 2G … 4G standards and will remain for new standards like 5G. Important difference is, that new standard 5G will operate in an extended frequency range, thus requiring typically higher density of base stations. With Figure 1 the principle structure of such a communication cell is shown.

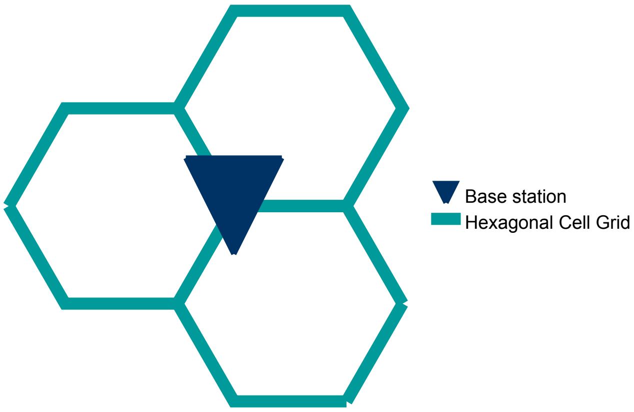


Figure 1 Hexagonal shaped mobile communication cell

More details concerning the geometrical relations are given with Figure 2. In order to allow well defined geometrical and spatial relations, in this study the distance between to neighbouring base stations is normalized to 1m. All other distances are related to this normalised inter site distance (ISD).

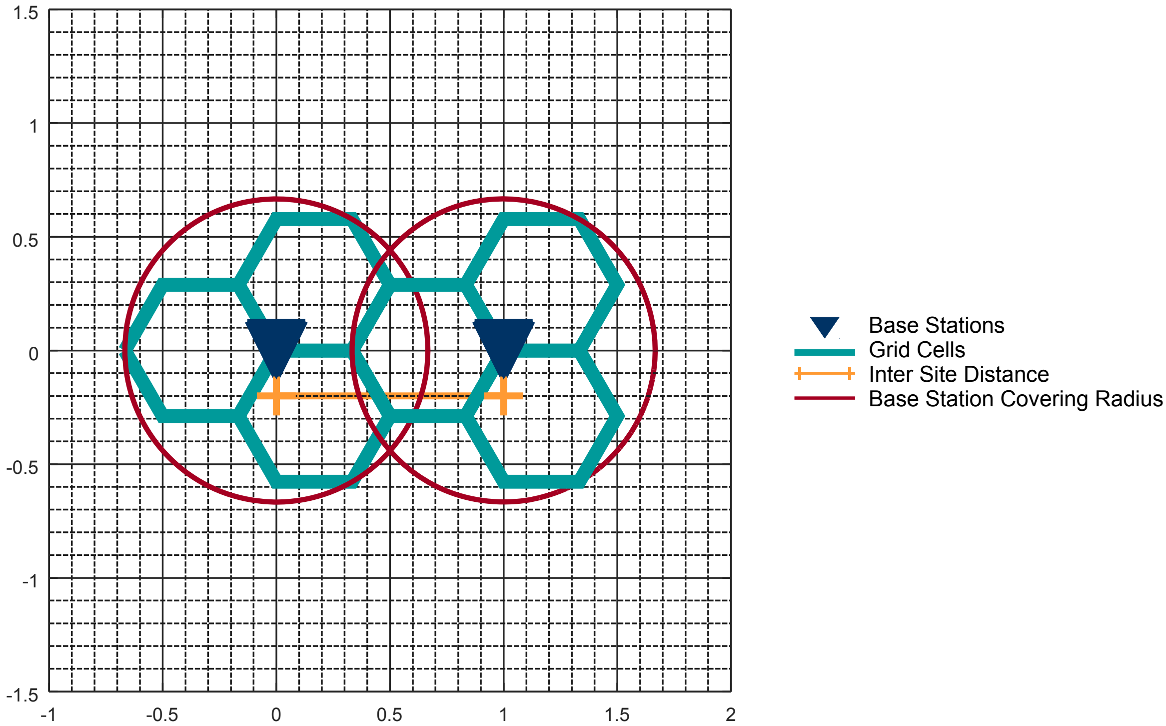


Figure 2 Communication grid cells, geometrical relations

One specific characteristic of such hexagonal grids is, that spatially equal distances between base stations can be realized. This simplifies network architecture tasks in terms of telecommunication engineering and in the end in terms of EMI investigations as well. Further geometrical relations with respect to the chosen normalisation

$$\text{inter site distance} = 1 \tag{2}$$

are given by

$$\text{hexagon edge length} = {}^{1}/_{3} \tag{3}$$

$$\text{hexagon circum radius} = {}^{1}/_{3} \tag{4}$$

$$\text{hexagon inner radius} = {}^{1}/_{3} \cdot \frac{\sqrt{3}}{2} \tag{5}$$

$$\text{base station coverage radius} = {}^{1}/_{3} \cdot 2 \tag{6}$$

$$\text{hexagon cell coverage area} = \left({}^{1}/_{3}\right)^{2} \cdot \frac{3}{2} \cdot \sqrt{3} = \frac{\sqrt{3}}{6} \tag{7}$$

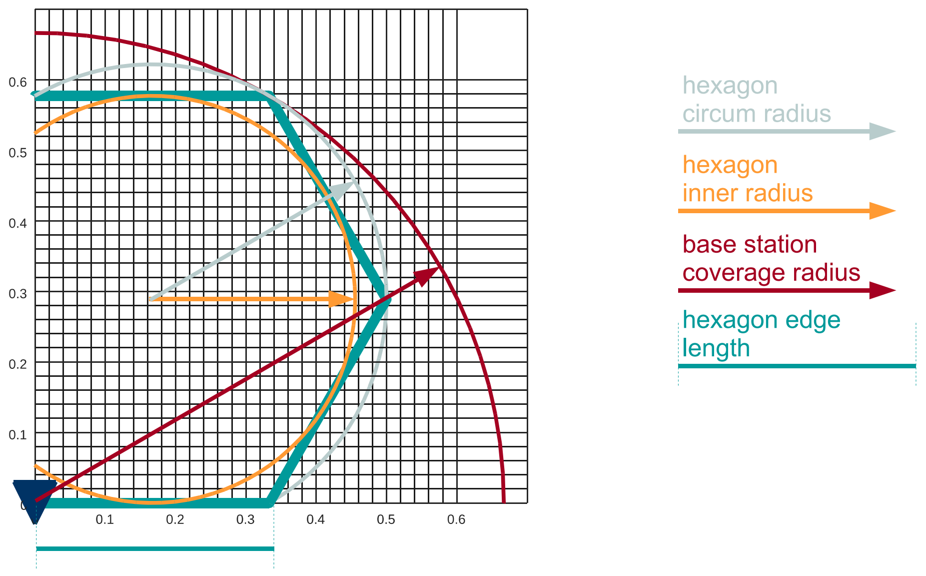


Figure 3 Communication Grid cells, geometrical relations

The red marked “base station coverage radius” represents a circular area that encloses three hexagonal cells around a central base station.

2.4 Basics of radio wave transmission

There are three principal modes for the transport of electromagnetic energy by means of radiation [3]

- Ground Waves,
- Tropospherical Waves and
- Space (Ionospheric) Waves.

The practical usability of these three transport modes is essentially depending on the frequency. Very low frequency waves transport their energy by means of ground waves only. With increased frequency (~ 1MHz) substantial part of the energy is transmitted by means of space waves. With increased frequency (10 … 30 MHz) the ground wave portion is getting more and more irrelevant due to massive attenuation. Certain frequency ranges especially in the range 2 to 25 MHz do make use of specific reflection (or more precise refraction) mechanisms due to the earth ionosphere allowing for extremely high ranges of radio links by means of multi reflection paths of the space waves between earth surface and ionosphere. For higher frequencies these effects are irrelevant because they are not reflected but transmitted through the ionosphere radiating into the universe. Therefore in the high frequency range (> 300 MHz) one has to consider direct line of sight (LOS) space waves only. If direct line is (partially) blocked the signals are attenuated, nevertheless certain portion of the energy will be overcome the obstacles by means of diffraction and/or (multipath) reflection. For very high frequency ranges (> 15 GHz) one has to consider another attenuation mechanism that is governed by molecule resonances (e.g. H_2O resonance around 25 GHz) that absorb certain parts of the em energy.

For the frequency range being relevant for this study, 450 MHz – 6 (100) GHz, we will focus on LOS space waves, neglecting additional attenuations due to molecule resonances.

Concerning the technical relevant basics for wave propagation, we will focus on plane far field waves, i.e. we assume that there is a certain distance between the receiving point and the wave emitting point. For such a plane wave *E* and *H* fields are perpendicular one to each other and are related in quantity by the free space impedance Z_0:

$$Z_0 = \frac{E}{H} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120 \cdot \pi \approx 377\ [\Omega] \tag{8}$$

Moreover the two field vectors *E* and *H* are perpendicular to the direction of radiated energy propagation, i.e. the pointing vector *S*.

$$S = E \times H = \frac{E^2}{Z_0}\ [\mathrm{W/m^2}] \tag{9}$$

Assuming a transmitter Tx being located at a central point and a spherical area around this centre, see Figure 4, the power density on this sphere will decrease with the distance (sphere radius) R squared:

$$S = \frac{P_{\mathrm{Tx}}}{4 \cdot \pi \cdot R^2} \tag{10}$$

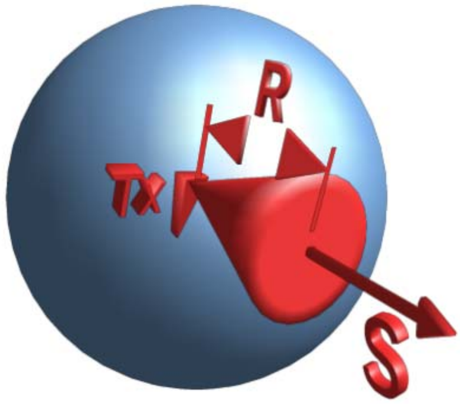


Figure 4 Transmitting station Tx at central point, power density S decreasing with distance R (radius of a sphere around this central point). The pointing vector S also illustrates the radial direction towards the wave is propagating and thus transporting its em energy.

Resulting from equations (9) and (10), the *E* fields will decrease linear with the distance accordingly: *E*~1/*r*.

2.5 Basics of free space propagation

Based on the assumption that only frequency ranges are of interest where LOS propagation is relevant, one has to consider an area limited by the radio horizon:

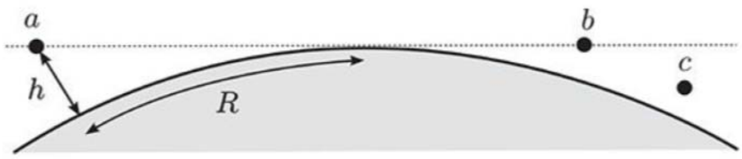


Figure 5 Radio Horizon (taken from [4]) for an antenna located at point a. Point b shares the radio horizon with point a, whereas point c is below the radio horizon of point a.

A rule of thumb for the extension of this radio horizon is given by [4]:

$$R = 4.12\ \text{km}\sqrt{\frac{h}{1\ \text{m}}} \tag{11}$$

where *h* is the height of the antennas (Tx and Rx) above the average terrain height.

The origin of this rule of thumb can be clarified by applying standard geometric considerations for segments of a circle. With the median earth radius equals to *r* = 6371 km (Wikipedia) and making use of standard geometry formulas for the calculation of circular segments:

$$\begin{gathered} r = \frac{\left(\frac{C}{2}\right)^2 + h^2}{2 \cdot h} = \frac{h}{2} + \frac{C^2}{8 \cdot h}, \\ C = \sqrt{8 \cdot r \cdot h - 4 \cdot h^2} = 2 \cdot r \cdot \sin\frac{\alpha}{2}, \\ R = \frac{r \cdot \pi \cdot \alpha}{180}, \end{gathered} \tag{12}$$

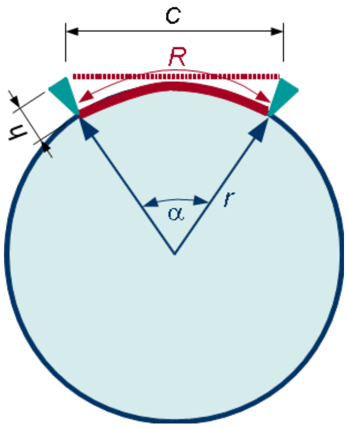


Figure 6 Circle segment calculation. (r: radius, α: angle with respect to opposite Tx and Rx position, h: height of Rx and Tx antenna, C: chord length, R: arc length)

and with the approximations

$$r - \frac{h}{2} \approx r \quad \text{and} \quad \operatorname{asin}\frac{\sqrt{8 \cdot h \cdot r}}{2 \cdot r} \approx \frac{\sqrt{8 \cdot h \cdot r}}{2 \cdot r}, \tag{13}$$

one results in

$$R = \frac{\sqrt{r} \cdot 2 \cdot \pi \cdot \sqrt{2}}{180} \cdot \sqrt{h} = 3.94 \text{ km} \sqrt{h}. \tag{14}$$

Explanation for the deviation 3.94 km against 4.12 km in the literature formula is explained with the term “radio horizon”. Compared to the value for the “horizon of sight” (~3.94 km) the radio horizon (~4.12 km) is slightly extended, because radio waves are slightly bended towards the ground by means of the atmosphere [3].

2.6 Field Accumulation – Base station dense urban scenario

A threat analysis due to accumulated fields from multiple base stations is given with this chapter. The following assumptions were used:

- Dense Urban e-MBB environment (ITU-R M.2412-0, [6])
    - o Base station (BS) and air vehicle height = 25 m
    - o Inter-site distance (ISD) · 1 m = 200 m
    - o Initial field strength (IFS) = 61 V/m
- Accumulated field strength scenario (worst case assumption):
    - o All base stations make use of the same frequency
    - o All fields interfere constructive (in phase)
    - o The "horizon" for BS seen by the air vehicle is set equals to 20.6 km, see equation (11). Therefore a radius of 103 · ISD (103 layers) has to be considered.

The given assumptions result in the following accumulated field strength:

On the circumference with radius ISD = 200 m one finds 6 neighbouring BS. Moreover in the region limited by > 1 · ISD … < 2 · ISD one finds additional 6 BS. In order to keep things simple, all twelve surrounding stations are assumed to be located in a distance of 1 · ISD of the centre station.

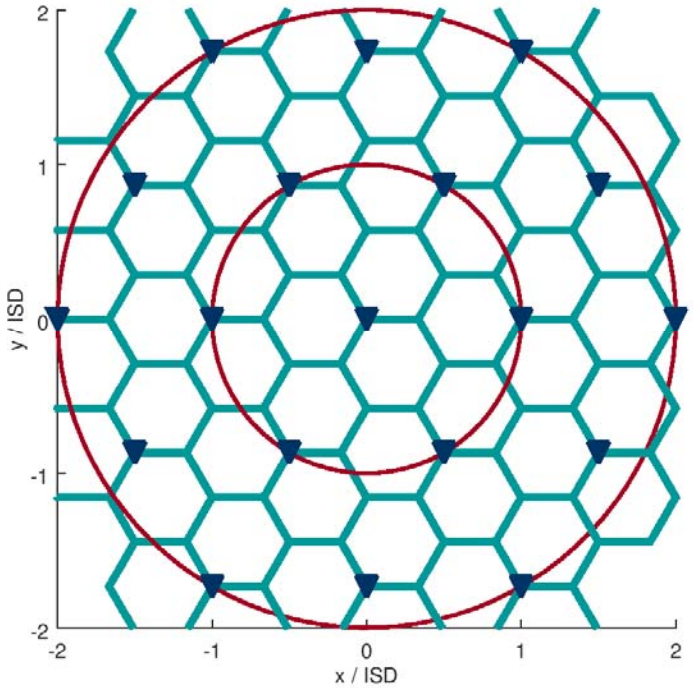


Figure 7 Base stations in area layers up to n ≤ 2 · ISD.

Thus the additional amount of field quantities is given by

$$E_{\mathrm{Add\_1}} = 12 \cdot \frac{\mathrm{IFS}}{\mathrm{ISD}} = 12 \cdot \frac{61\ \mathrm{V/m}}{200} = 3.66\ \mathrm{V/m} \qquad (15)$$

Next step takes into account additional BS in the area ≥ 2 · ISD … < 3 · ISD. On the circumference with radius ISD = 400 m one finds 6 neighbouring BS. Moreover in the region limited by > 2 · ISD … < 3 · ISD one finds additional 12 BS. Again all additional BS are assumed to be located at the nearest distance, i.e. 2 · ISD

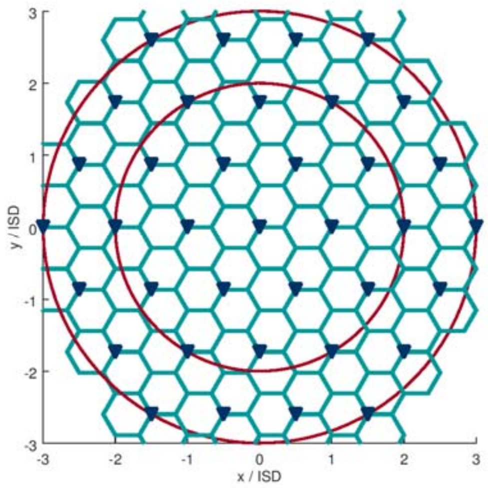


Figure 8 Base stations in area layers up to ≤ 3 · ISD

Thus the additional amount of field quantities is given by

$$E_{\text{Add\_2}} = 18 \cdot \frac{\text{IFS}}{2 \cdot \text{ISD}} = 18 \cdot \frac{61\ \text{V/m}}{400} = 2.745\ \text{V/m} \tag{16}$$

Obviously, the next step takes into account additional BS in the area ≥ 3 · ISD … < 4 · ISD. On the circumference with radius = ISD = 600 m one finds 6 neighbouring BS and in the region limited by > 3 · ISD … < 4 · ISD one finds additional 18 BS. Again all additional BS are assumed to be located at the nearest distance, i.e. 3 · ISD.

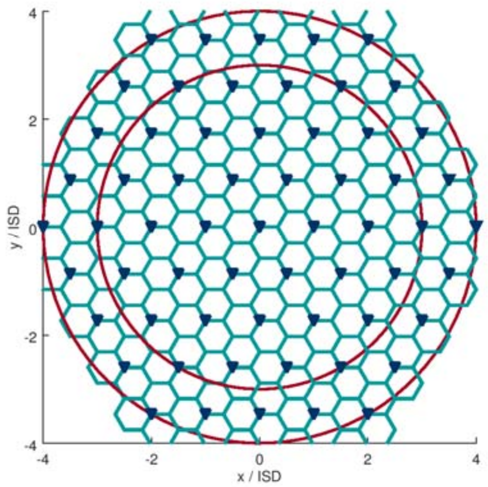


Figure 9 Base stations in area layers up to ≤ 4 · ISD

Thus the additional amount of field quantities is given by

$$E_{\text{Add\_3}} = 24 \cdot \frac{\text{IFS}}{3 \cdot \text{ISD}} = 24 \cdot \frac{61\ \text{V/m}}{600} = 2.440\ \text{V/m} \tag{17}$$

In a last detailed step the additional area layer ≥ 4 · ISD … < 5 · ISD is investigated. Again 6 BS are located on the circumference 4 · ISD and additional 24 BS are within the area 4 to 5 times ISD.

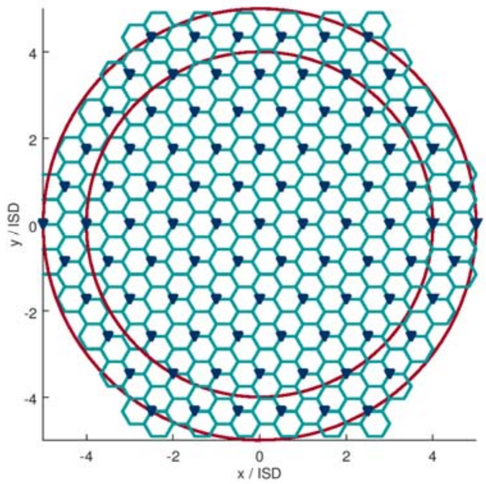


Figure 10 Base stations in area layers up to ≤ 5 · ISD

Additional amount of field quantities is given by

$$E_{\text{Add\_4}} = 30 \cdot \frac{\text{IFS}}{4 \cdot \text{ISD}} = 30 \cdot \frac{61\ \text{V/m}}{800} = 2.288\ \text{V/m} \tag{18}$$

From the given investigation of the distances up to 5 · ISD, one can derive empirical formulas for any amount of ISD distance:

$$E_{\text{Add\_}n} = 6 \cdot (n+1) \cdot \frac{\text{IFS}}{n \cdot \text{ISD}} \tag{19}$$

where the integer number *n* denotes the number of area layers with radius ISD around the centre. Hence the total amount of neighbouring BS (NBS) up to the “horizon” that has to be considered is given by

$$\text{NBS} = \sum_{n=1}^{103} 6 \cdot (n+1) = 32754 \tag{20}$$

Here the “horizon” determines the upper limit of the sum: 21 km / ISD = 21 km / 200 m = 105. Furthermore the total amount of additional field (TAAF) is given by

$$\text{TAAF} = \sum_{n=1}^{103} 6 \cdot (n+1) \cdot \frac{\text{IFS}}{n \cdot \text{ISD}} = 198.04\ \text{V/m} \tag{21}$$

The individual and integral behaviour of the TAAF is shown in Figure 11.

Finally the resulting entire field strength (ETF) of the worst case estimation is given by

$$\text{ETF} = \text{IFS} + \text{TAAF} = \text{IFS} \cdot \left[1 + \sum_{n=1}^{103} \frac{6 \cdot (n+1)}{n \cdot \text{ISD}}\right] = 61\ \text{V/m} \cdot [1 + 3.247] = 259.07\ \text{V/m} \tag{22}$$

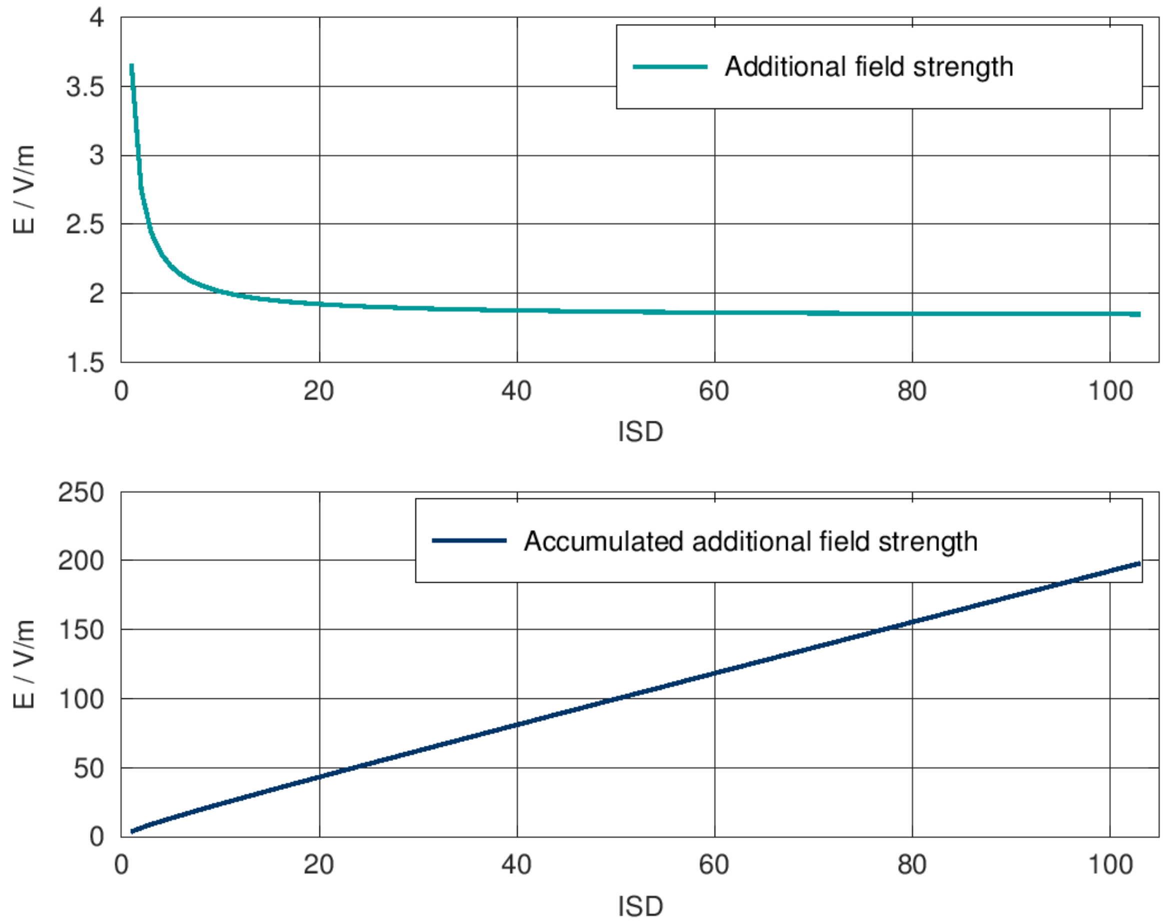


Figure 11 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring base stations. The x-axis unit is given with multiples of distance radius between centre base station and neighbouring base stations (ISD). One ISD is equal to 200 m.

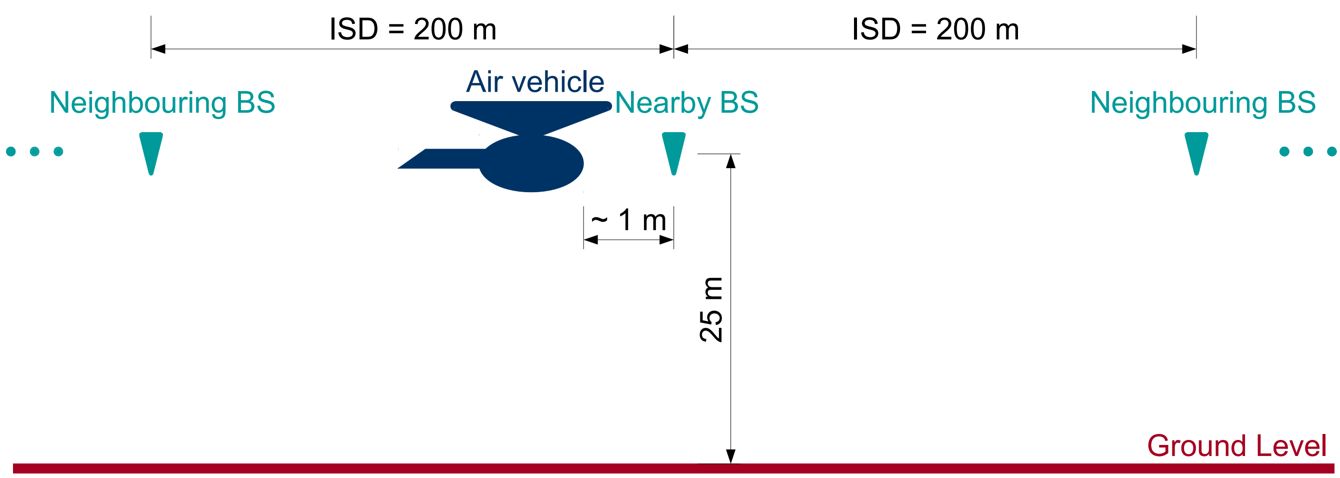


Figure 12 Geometrical arrangement: IFS due to nearby base station: 61 V/m, ISD = 200 m. TAAF due to neighbouring base stations (Σ_{NBS} = 32754) up to the radio horizon (20.6 km): 198 V/m

2.7 Field Accumulation – Base station rural scenario

This environment is characterized by a larger distance between individual base stations, a typically larger antenna height and an increased transmit power of the stations, compared to the urban environment. The following assumptions were used:

- Rural e-MBB environment (ITU-R M.2412-0, [6])
  - Base station (BS) and air vehicle height = 35 m
  - Inter-site distance (ISD) · 1 m = 1732 m
  - Initial field strength (IFS) = 108.5 V/m
- Accumulated field strength scenario (worst case assumption):
  - All base stations make use of the same frequency
  - All fields interfere constructive (in phase)
  - The “horizon” for BS seen by the air vehicle is set equals to 25 km, see equation (11). Therefore a radius of 15 · ISD (15 layers) has to be considered.

Total amount of neighbouring BS (NBS) up to the “horizon” that have to be considered is given by

$$\mathrm{NBS} = \sum_{n=1}^{15} 6 \cdot (n+1) = 810 \tag{23}$$

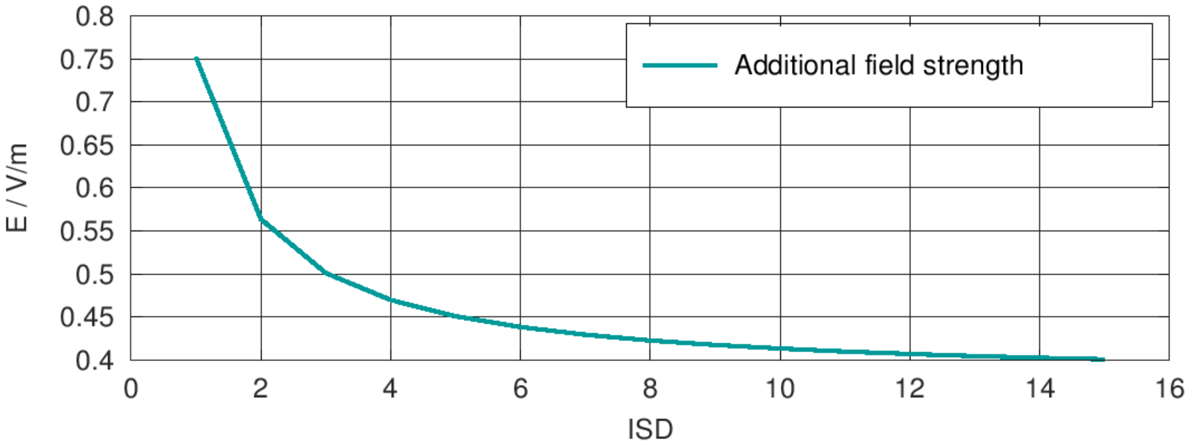
Total amount of additional field (TAAF) is given by

$$\mathrm{TAAF} = \sum_{n=1}^{15} 6 \cdot (n+1) \cdot \frac{\mathrm{IFS}}{n \cdot \mathrm{ISD}} = 6.89\ \mathrm{V/m} \tag{24}$$

The individual and integral behaviour of the TAAF is shown in Figure 11.

Finally the resulting entire field strength (ETF) of the worst case estimation is given by

$$\mathrm{ETF} = \mathrm{IFS} + \mathrm{TAAF} = 108.5\ \mathrm{V/m} + 6.89\ \mathrm{V/m} = 115.39\ \mathrm{V/m} \tag{25}$$



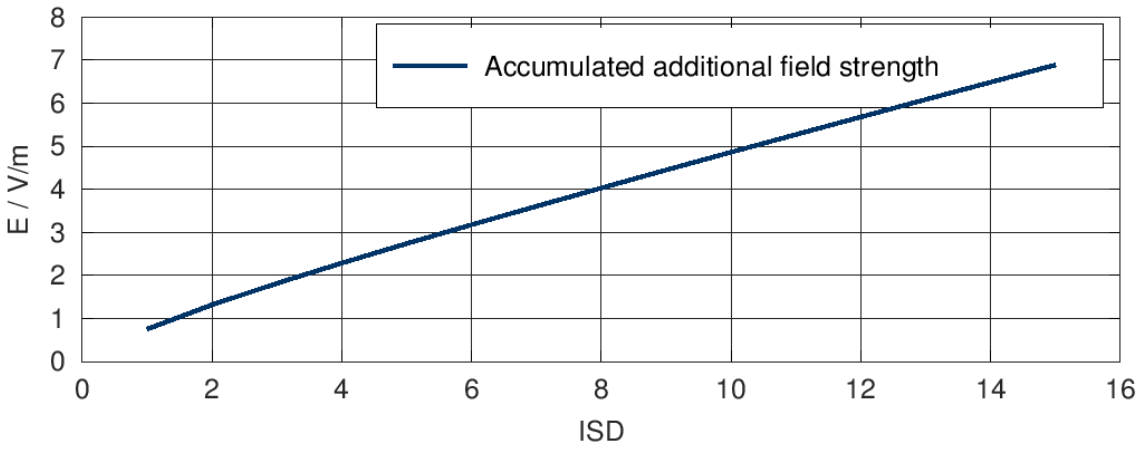


Figure 13 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring base stations. The x-axis unit is given with multiples of distance radius between centre base station and neighbouring base stations. One ISD is equal to 1732 m.

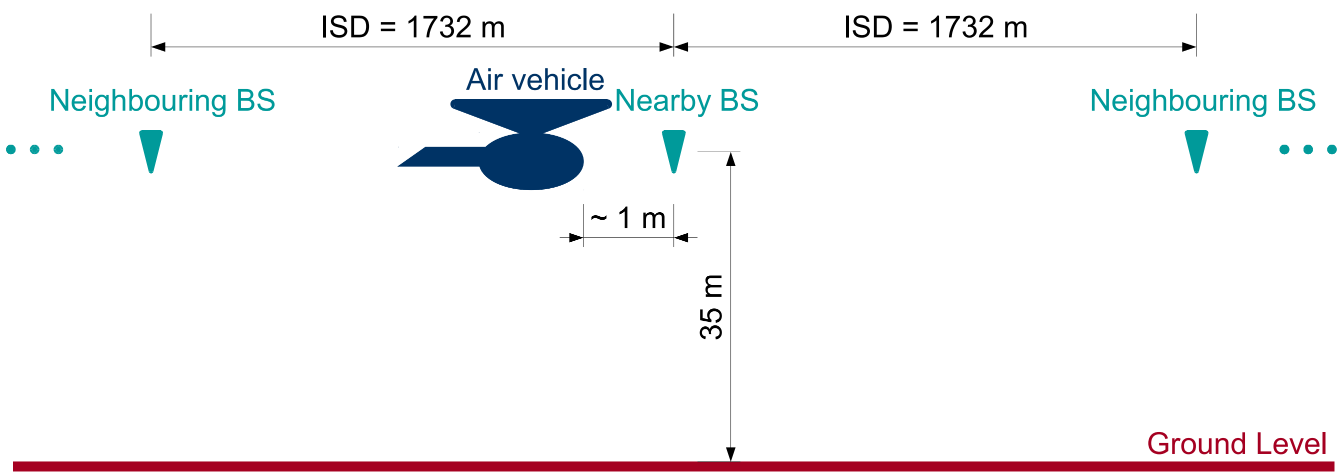


Figure 14 Geometrical arrangement: IFS due to nearby base station: 108.5 V/m, ISD = 1732 m. TAAF due to neighbouring base stations (Σ_{NBS} = 810) up to the radio horizon (25 km): 6.9 V/m

2.8 Field Accumulation – User equipment scenario

The basis for the presented user equipment scenarios is the assumption that up to 1’000’000 user equipments (UE) per km^2 might be applied [8]. Mapping this figure to the here used hexagon cell approach, the resulting distance between two UE can be assumed to be 0.981 m. The following assumptions were used:

- UE environment
  - User equipment (UE) and air vehicle height* = 1.5 m
  - Inter-site distance (ISD) · 1 m = 0.981 m
  - Initial field strength (IFS) = 3 V/m
- Accumulated field strength scenario (worst case assumption):
  - All user equipment make use of the same frequency
  - All fields interfere constructive (in phase)
  - The “horizon” for UE seen by the air vehicle is set equals to 5.046 km, see equation (11). Therefore a radius of 5144 · ISD has to be considered.

Total amount of neighbouring UE (NUE) up to the “horizon” that have to be considered is given by

$$\mathrm{NUE} = \sum_{n=1}^{5144} 6 \cdot (n+1) = 79.429 \cdot 10^6 \qquad (26)$$

Total amount of additional field (TAAF) is given by

$$\mathrm{TAAF} = \sum_{n=1}^{5144} 6 \cdot (n+1) \cdot \frac{\mathrm{IFS}}{n \cdot \mathrm{ISD}} = 94553^{**}\ \mathrm{V/m} \qquad (27)$$

The individual and integral behaviour of the TAAF is shown in Figure 11.

Finally the resulting entire field strength (ETF) of the worst case estimation is given by (23)

$$\mathrm{ETF} = \mathrm{IFS} + \mathrm{TAAF} = 3\ \mathrm{V/m} + 109220\ \mathrm{V/m} = 94553^{**}\ \mathrm{V/m} \qquad (28)$$

* Remark 1: A more realistic scenario, where the user equipments are located in 1.5 m height and the air vehicle is located in 25 m height is investigated with chapter 3.4.

**: Remark 2: These are hypothetical values only. Realistic and technical meaningful values are presented with chapters and 3.2.3. and 3.3.2.

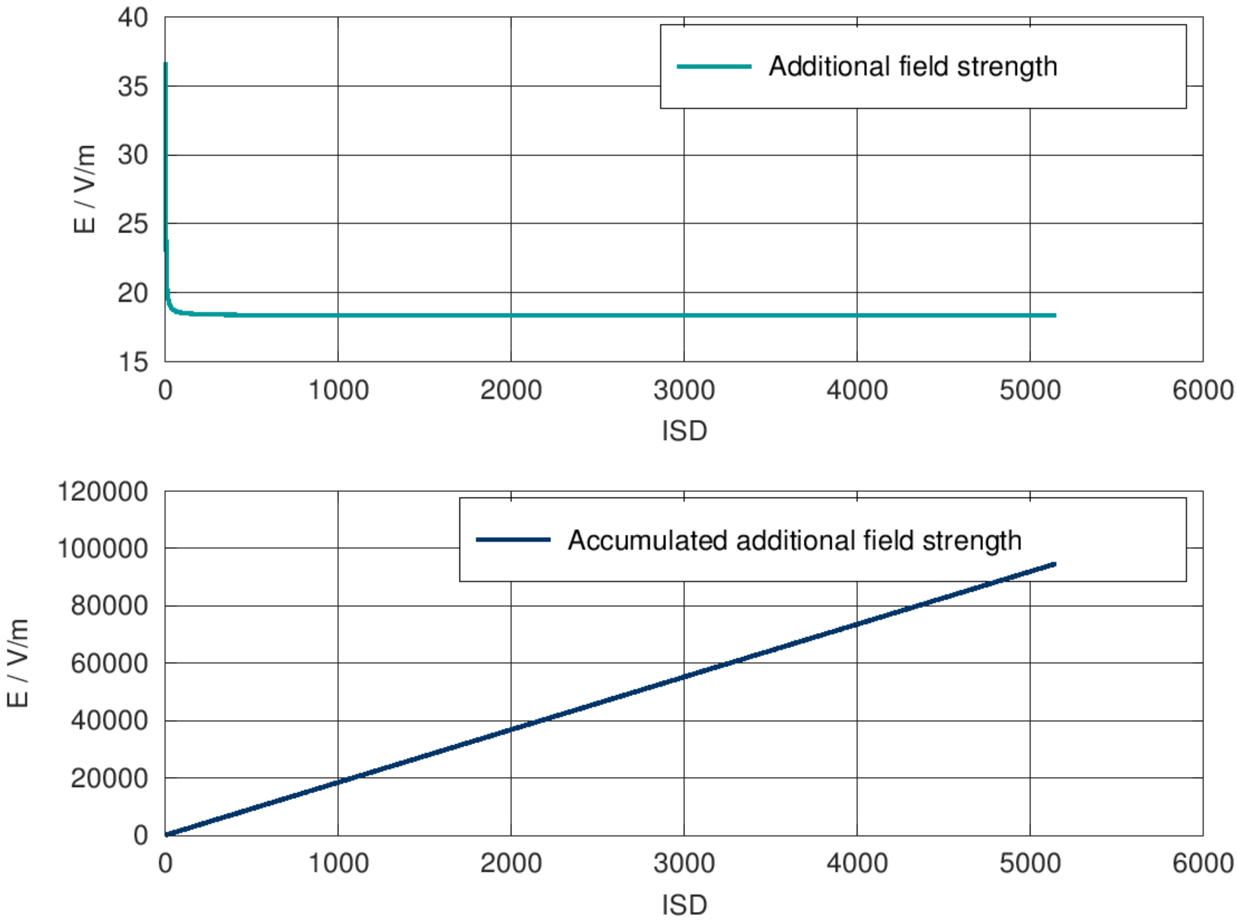


Figure 15 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring user equipments. The x-axis unit is given with multiples of distance radius between centre user equipment and neighbouring user equipments.
One ISD is equal to 0.981 m.

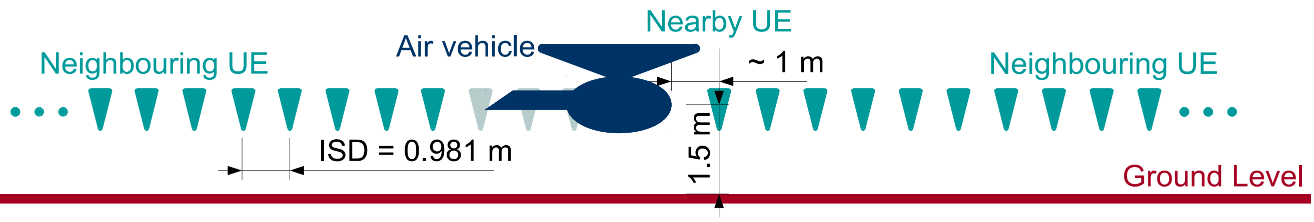


Figure 16 Geometrical arrangement: IFS due to nearby user equipment: 3 V/m, ISD = 0.981 m. TAAF due to neighbouring base stations (Σ_{NBS} = 79.429·10^6) up to the radio horizon (5.045 km): 94553 V/m

3 Field Accumulation – Advanced Approaches

The very simple calculations, presented in the previous chapters, assume scalar constructive superposition of all fields due to new telecommunication infrastructure and devices. Fortunately, in terms of EMI, these superposition scenarios are impractical. More realistic superposition quantities are limited, especially due to the hereafter listed physical and technical reasons:

- A purely scalar superposition of field strength is not in accordance with physics. It can be assumed only for superposition of strictly monochromatic fields [11], i.e. fields that are oscillating at a single frequency and moreover the field incoming directions have to be considered by means of an interference term. This results in doing the field superposition by means of vector summarizing.
- Network architecture of base station arrangements has to be realized in a manner, that neighbouring stations will never operate at the same frequency band at the same time. This fact clearly reduces the number of stations that have to be considered for the TAAF calculation.
- The assumption that the fields are propagating undisturbed in free field (LOS) condition being attenuated by $1/r$ and the energy is decreased by $1/r^2$ is unrealistic. More realistic path loss models as given by [6] assume energy attenuations of $1/r^3$ to $1/r^5$ for dense urban environments. This is due to blocking, diffraction and attenuating effects of different objects.
- For the user equipment scenario the assumption that 1’000’000 devices / km^2 are visible for a potential victim of EMI is not realistic. One has to consider, that according to [6], at least 80 % of this devices will be operated indoor. Therefore relevant attenuation from in- to outdoor has to be considered. Moreover many of these devices will be used for IOT purposes, with a duty cycle of one message / 2 hours or only one message / day. Therefore a certain statistical assumption is appropriate, limiting the number of devices which might operate on the same frequency in a common time slot.

The here listed physical principles and technical details and their impact on a more realistic field accumulation for the different scenarios (dense urban, rural and user equipment) will be presented in the following subchapters.

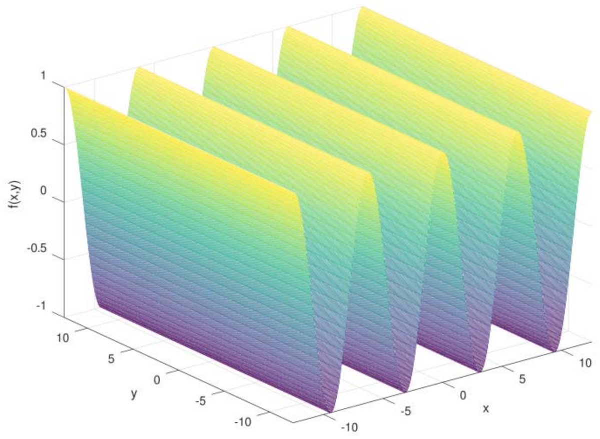
3.1 Field Accumulation – Vector approach

The difference concerning this approach for resulting *E*-field strength is visualized with the following figure, where two plane waves being perpendicular one to each other are interfering. The resulting field strength values are displayed with the lower pictures, in which the left one shows results for scalar accumulation of the fields

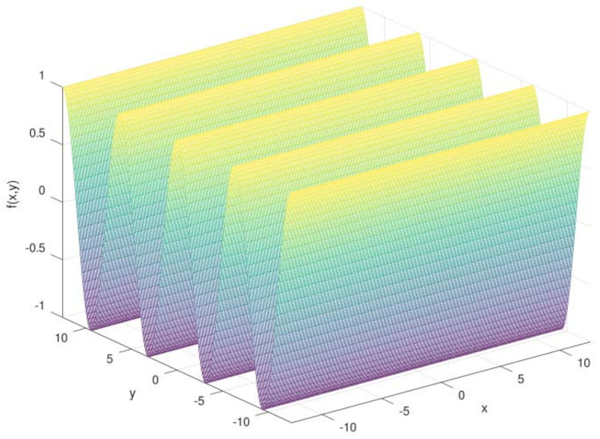
$$E = E_1 + E_2, \tag{29}$$

while the right hand side shows the result of vector accumulation, i.e.

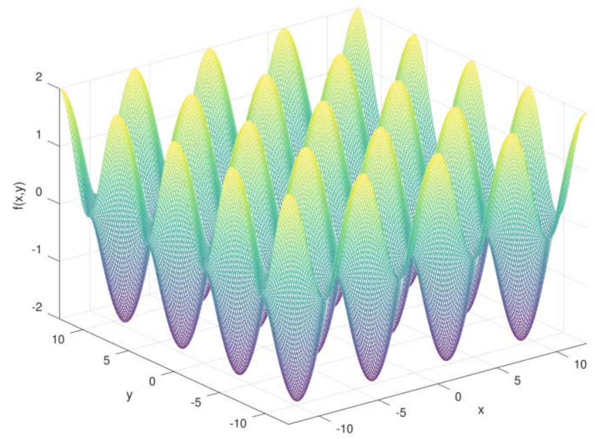
$$E = \sqrt{E_1^2 + E_2^2}\,. \tag{30}$$



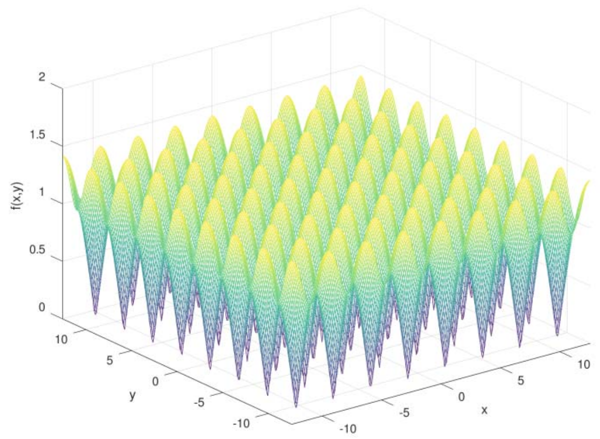
Wave 1



Wave 2



Scalar accumulation



Vector accumulation

Figure 17 Wave interference of two waves incoming from perpendicular directions, Wave 1 incoming from x-direction, Wave 2 from y-direction

Taken the vector related approach into account the empirical formulas for additional field strength are given by

$$E_{\mathrm{Add\_}n,\mathrm{VA}} = \frac{\mathrm{IFS}}{n \cdot \mathrm{ISD}} \cdot \sqrt{6 \cdot (n+1)}. \tag{31}$$

And also the applicable formula for the calculation of the additional field strength changes to

$$\mathrm{TAAF}_{\mathrm{VA}} = \sqrt{\sum_{n=1}^{m} E^2_{\mathrm{Add\_}n,\mathrm{VA}}} = \frac{\mathrm{IFS}}{\mathrm{ISD}} \cdot \sqrt{\sum_{n=1}^{m} \frac{6 \cdot (n+1)}{n^2}} \tag{32}$$

where the upper sum limit *m* denotes the relation radio horizon radius above ISD.

The application of vector accumulation (VA) reduces the amount of additional fields (TAAF) for the different scenarios as shown with the following subchapters.

3.1.1 Base station dense urban scenario (vector approach):

$$\mathrm{TAAF_{VA}} = 1.956\,\frac{\mathrm{V}}{\mathrm{m}} \text{ and } \mathrm{ETF_{VA}} = \sqrt{\mathrm{IFS}^2 + \mathrm{TAAF_{VA}^2}} = 61.031\,\frac{\mathrm{V}}{\mathrm{m}}. \tag{33}$$

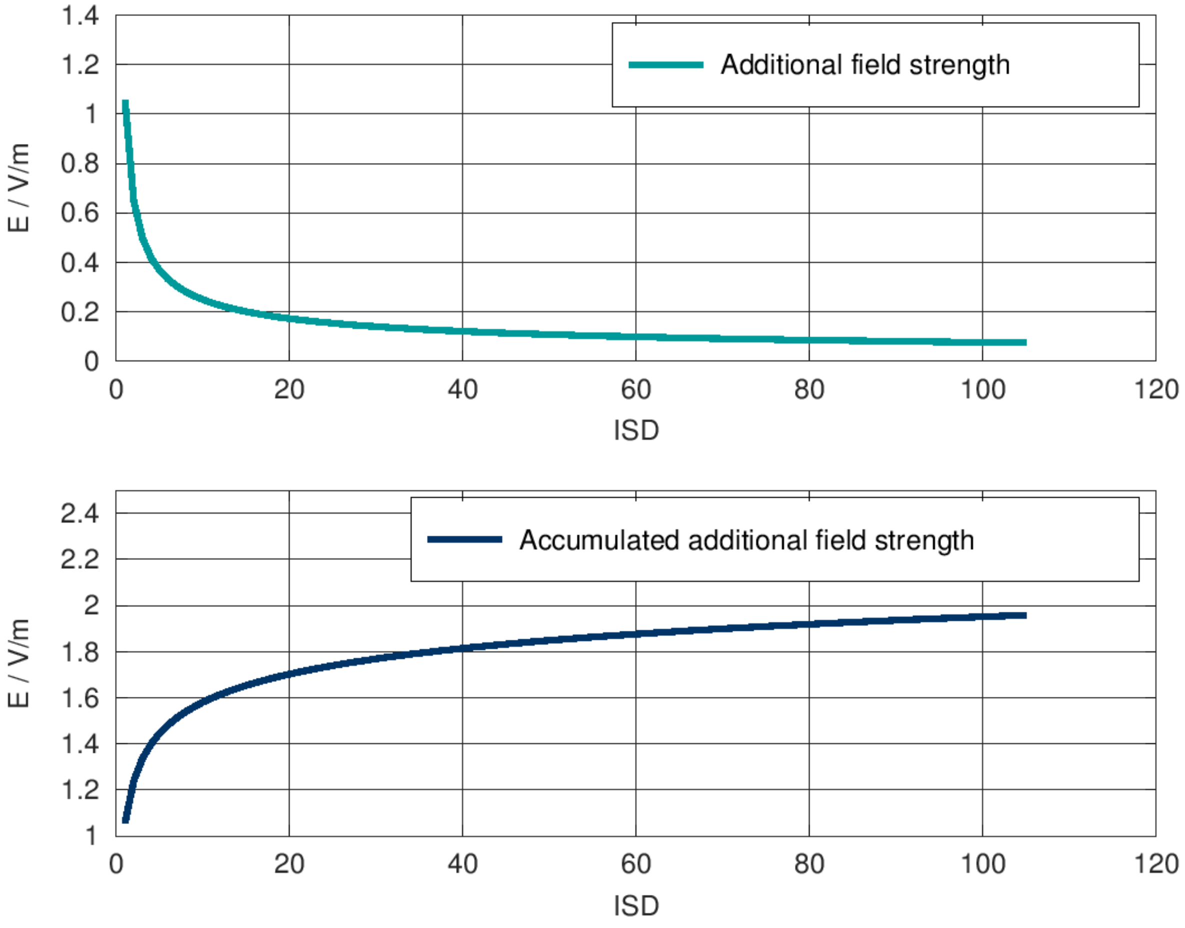


Figure 18 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring base stations. The x-axis unit is given with multiples of distance radius between centre base station and neighbouring base stations. Vector accumulation is used for field superposition. One ISD is equal to 200 m.

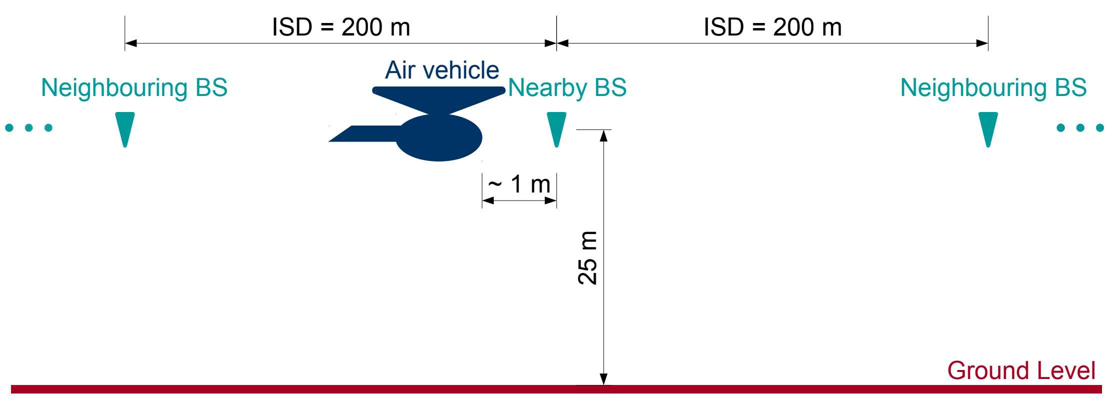
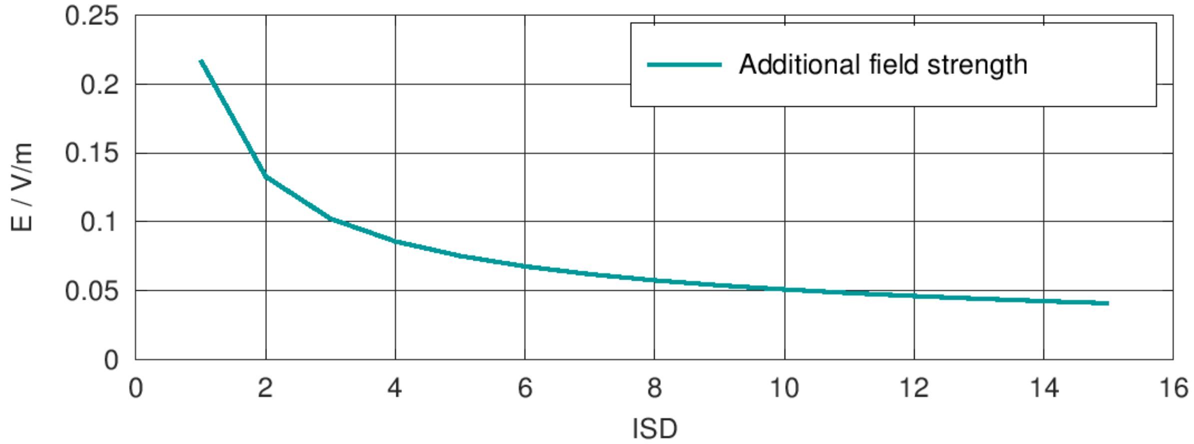


Figure 19 Geometrical arrangement: IFS due to nearby base station: 61 V/m, ISD = 200 m. $TAAF_{VA}$ due to neighbouring base stations (Σ_{NBS} = 32754) up to the radio horizon (20.6 km): 1.956 V/m

3.1.2 Base station rural scenario (vector approach):

$$\mathrm{TAAF_{VA}} = 0.339\,\frac{\mathrm{V}}{\mathrm{m}} \text{ and } \mathrm{ETF_{VA}} = \sqrt{\mathrm{IFS}^2 + \mathrm{TAAF}_{\mathrm{VA}}^2} = 108.5\,\frac{\mathrm{V}}{\mathrm{m}}. \quad (34)$$



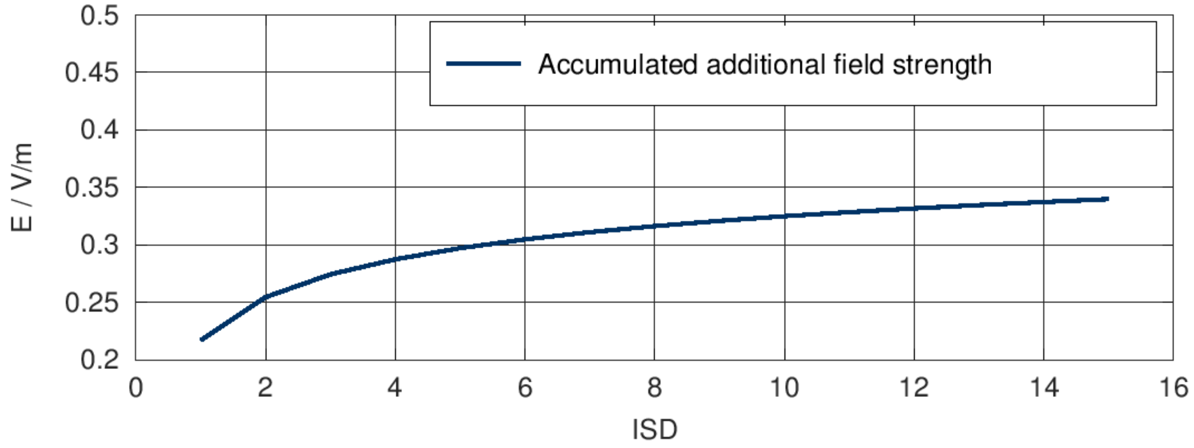


Figure 20 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring base stations. The x-axis unit is given with multiples of distance radius between centre base station and neighbouring base stations. Vector accumulation is used for field superposition. One ISD is equal to 1732 m.

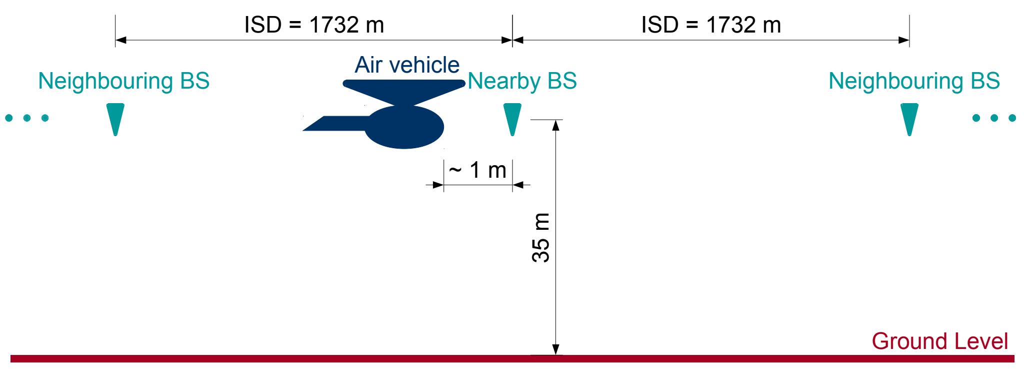


Figure 21 Geometrical arrangement: IFS due to nearby base station: 108.5 V/m, ISD = 1732 m. $TAAF_{VA}$ due to neighbouring base stations (Σ_{NBS} = 810) up to the radio horizon (24.4 km): 0.339 V/m

3.1.3 User equipment scenario (vector approach):

$$\mathrm{TAAF_{VA}} = 24.580\,\frac{\mathrm{V}}{\mathrm{m}} \text{ and } \mathrm{ETF_{VA}} = \sqrt{\mathrm{IFS}^2 + \mathrm{TAAF}_{\mathrm{VA}}^2} = 24.762\,\frac{\mathrm{V}}{\mathrm{m}}. \tag{35}$$

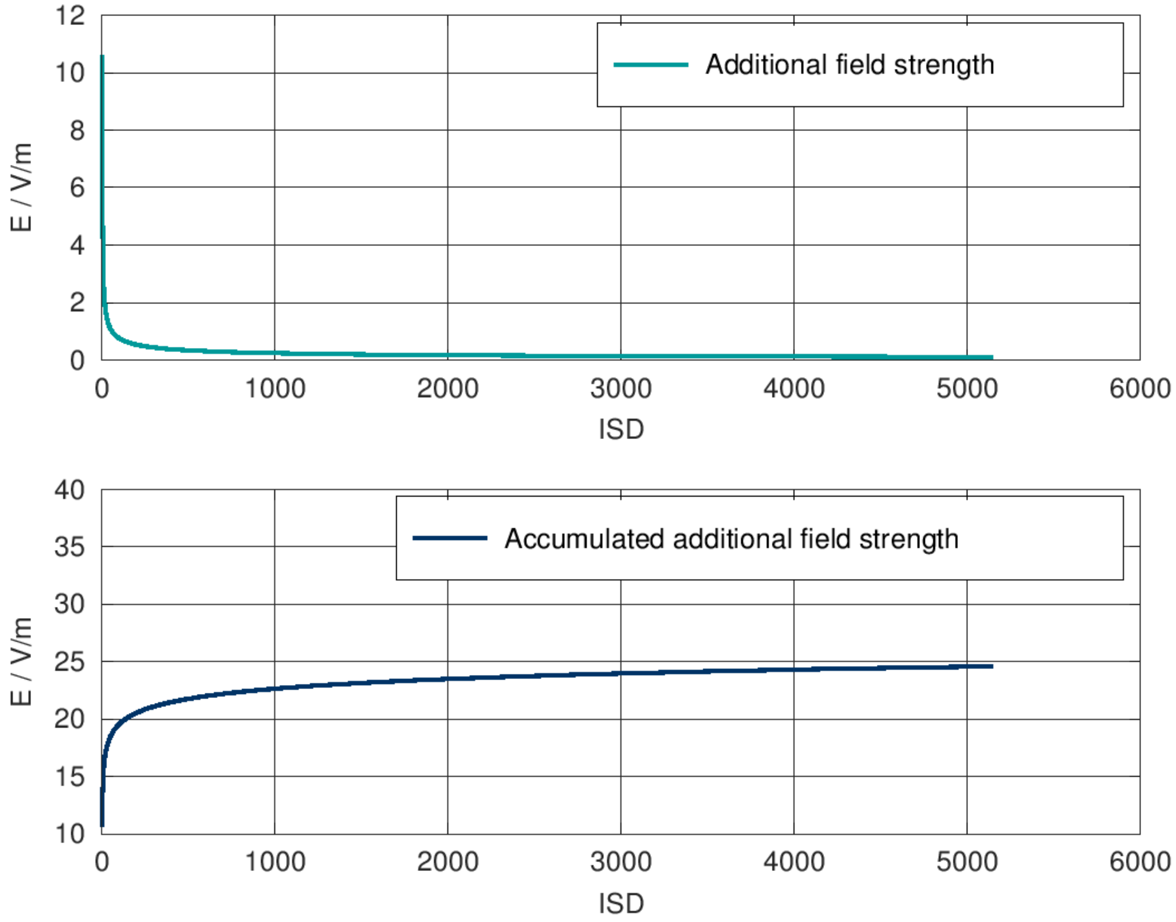


Figure 22 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring user equipments. The x-axis unit is given with multiples of distance radius between centre user equipment and neighbouring user equipments. Vector accumulation is used for field superposition. One ISD is equal to 0.981 m.

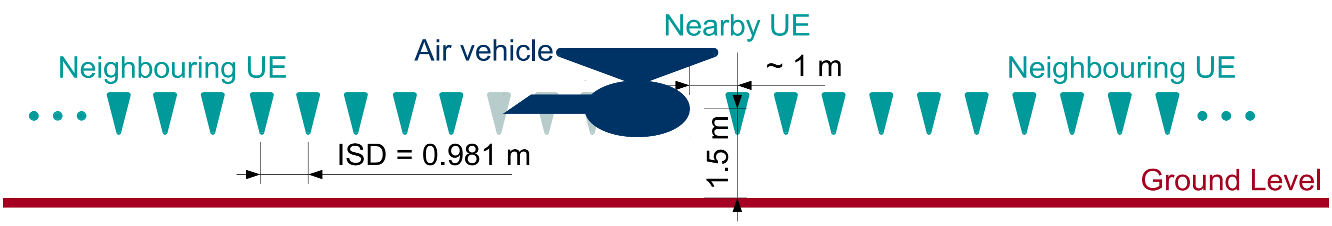


Figure 23 Geometrical arrangement: IFS due to nearby user equipment: 3 V/m, ISD = 0.981 m. TAAF due to neighbouring user equipments (Σ_{NUE} = 79.429·10^6) up to the radio horizon (5.045 km): 24.58 V/m

3.2 Field Accumulation - Network architecture related approach

For obvious reasons network planning for base stations will take care of the requirement that neighbouring stations shall not make use of the same frequency bands in a common time slot. At least the range circles (covering three hexagonal cells) of base stations using the same frequency bands at the same time shall not overlap! This requirement clearly reduces the number of stations that have to be considered for field accumulation, as shown here:

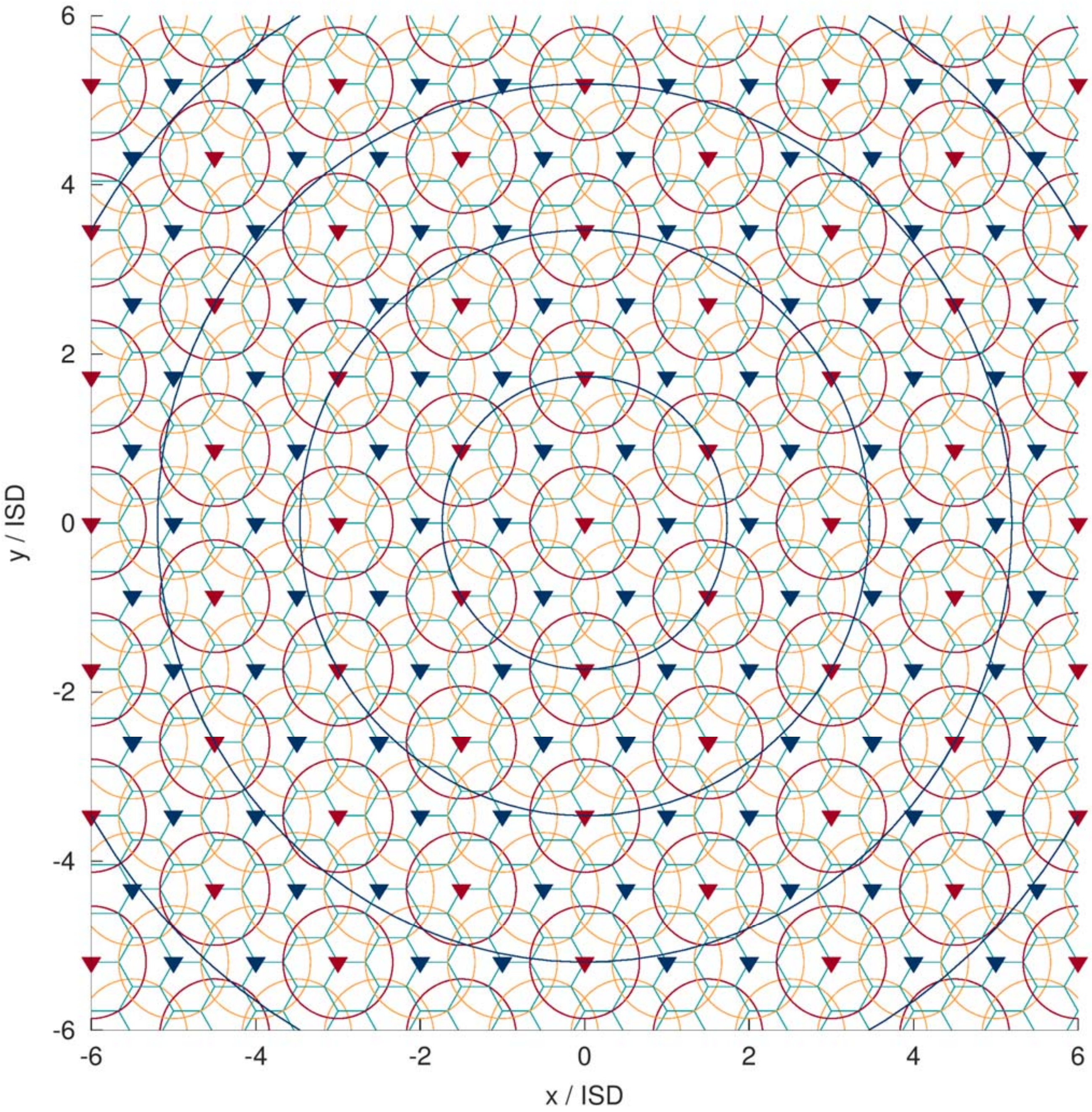


Figure 24 Base stations (red) with not overlapping ranges, using the same frequency, are marked with red circles. All other base stations (blue) are marked with orange coloured range circles. Additionally blue circles around the centre station are marking multiplies (1,2,3 and 4) of $\sqrt{3}$ times ISD.

Taken the network architecture related approach into account the empirical formulas for additional field strength are given by

$$E_{\mathrm{Add}\_n,\mathrm{VA},\mathrm{NA}} = \frac{\mathrm{IFS}}{n \cdot \mathrm{ISD} \cdot \sqrt{3}} \cdot \sqrt{6 \cdot (n+1)}. \quad (36)$$

And also the applicable formula for the calculation of the additional field strength changes to

$$\mathrm{TAAF}_{\mathrm{VA,NA}} = \sqrt{\sum_{n=1}^{m_{\mathrm{NA}}} E^2_{\mathrm{Add}\_n,\mathrm{VA}}} = \frac{\mathrm{IFS}}{\mathrm{ISD} \cdot \sqrt{3}} \cdot \sqrt{\sum_{n=1}^{m_{\mathrm{NA}}} \frac{6 \cdot (n+1)}{n^2}} \quad (37)$$

where the upper sum limit m_{NA} denotes the relation radio horizon radius above ISD $\cdot \sqrt{3}$.

The application of vector accumulation (VA) and network architecture (NA) approaches reduces the amount of additional fields (TAAF) for the different scenarios as shown with the following subchapters.

3.2.1 Base station dense urban scenario (vector and network approach):

$$\mathrm{TAAF}_{\mathrm{VA,NA}} = 1.083\,\frac{\mathrm{V}}{\mathrm{m}} \text{ and } \mathrm{ETF}_{\mathrm{VA,NA}} = \sqrt{\mathrm{IFS}^2 + \mathrm{TAAF}_{\mathrm{VA,NA}}^2} = 61.01\,\frac{\mathrm{V}}{\mathrm{m}}. \quad (38)$$

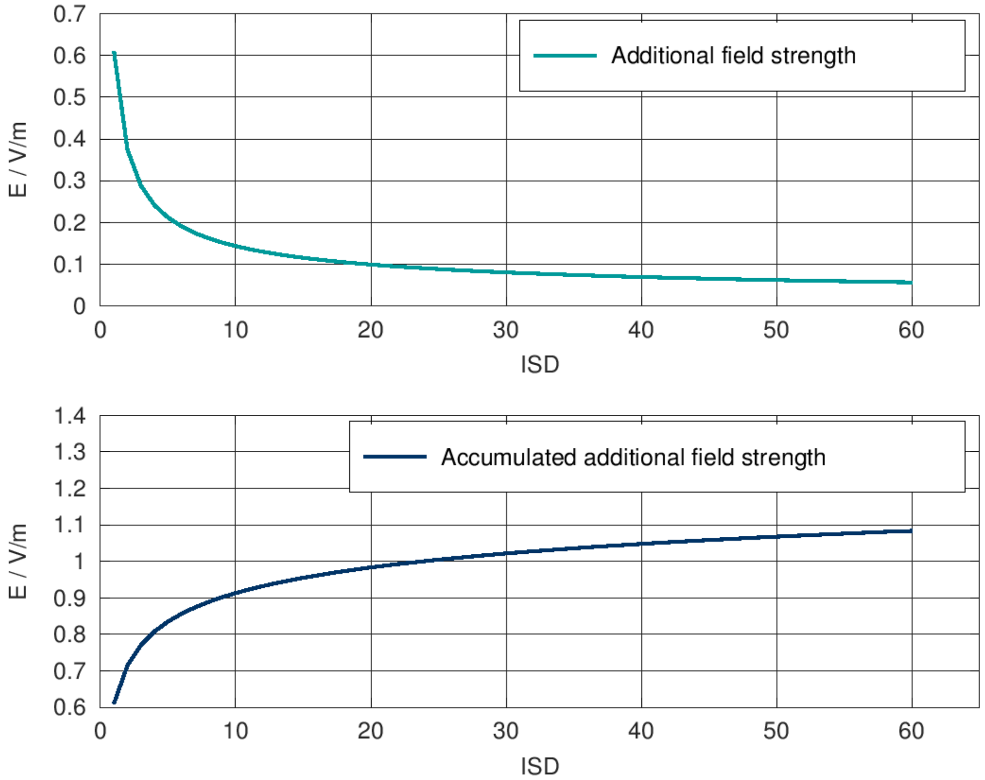


Figure 25 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring base stations. The x-axis unit is given with multiples of distance radius between centre base station and neighbouring base stations. Vector accumulation is used for field superposition. Network architecture is considered, presuming that neighbouring stations will not operate in the same frequency range. One ISD is equal to 200 · sqrt(3) m.

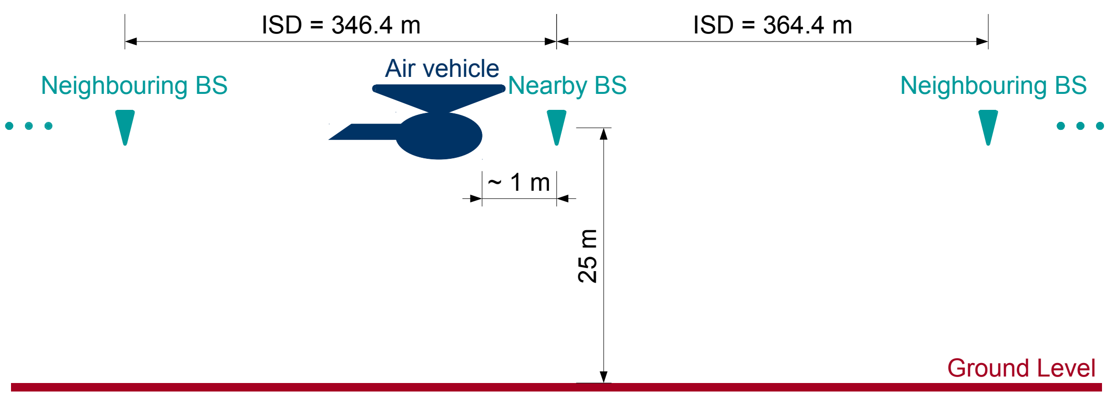


Figure 26 Geometrical arrangement: IFS due to nearby base station: 61 V/m, ISD = 346.4 m. $TAAF_{VA,NA}$ due to neighbouring base stations (Σ_{NBS} = 11340) up to the radio horizon (20.6 km): 1.083 V/m

3.2.2 Base station rural scenario (vector and network approach):

$$\mathrm{TAAF}_{\mathrm{VA,NA}} = 0.185\,\frac{\mathrm{V}}{\mathrm{m}} \text{ and } \mathrm{ETF}_{\mathrm{VA,NA}} = \sqrt{\mathrm{IFS}^2 + \mathrm{TAAF}^2_{\mathrm{VA,NA}}} = 108.50\,\frac{\mathrm{V}}{\mathrm{m}}. \tag{39}$$

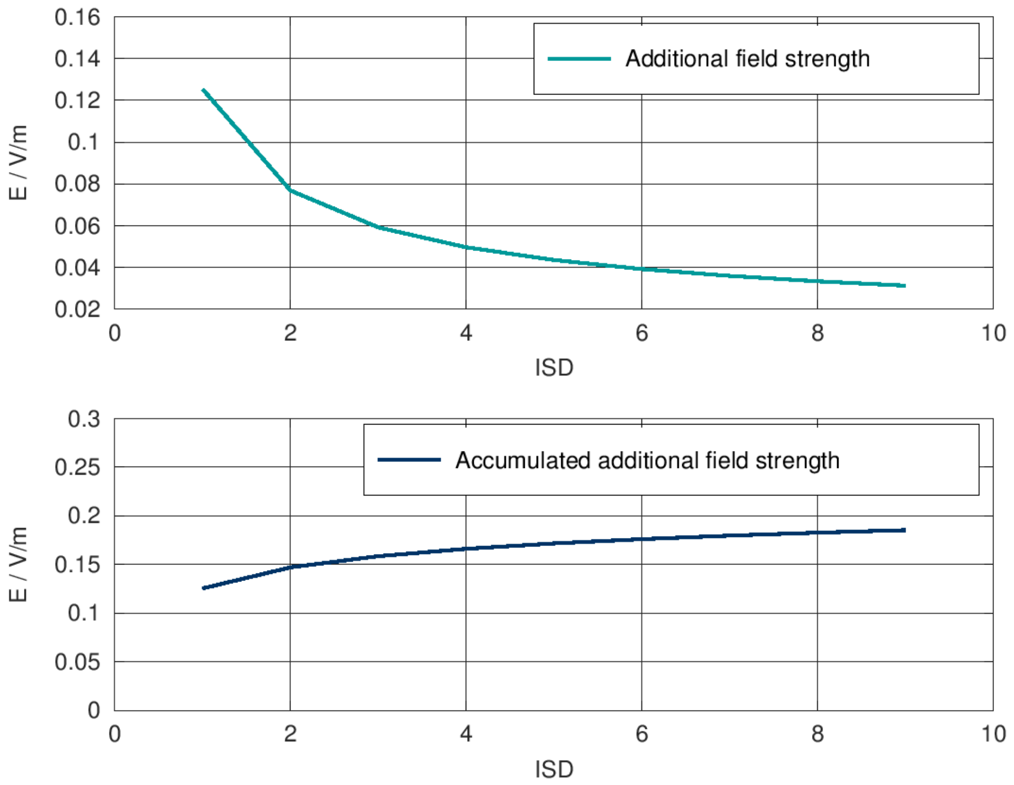


Figure 27 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring base stations. The x-axis unit is given with multiples of distance radius between centre base station and neighbouring base stations. Vector accumulation is used for field superposition. Network architecture is considered, presuming that neighbouring stations will not operate in the same frequency range.
One ISD is equal to 1732 · sqrt(3) m.

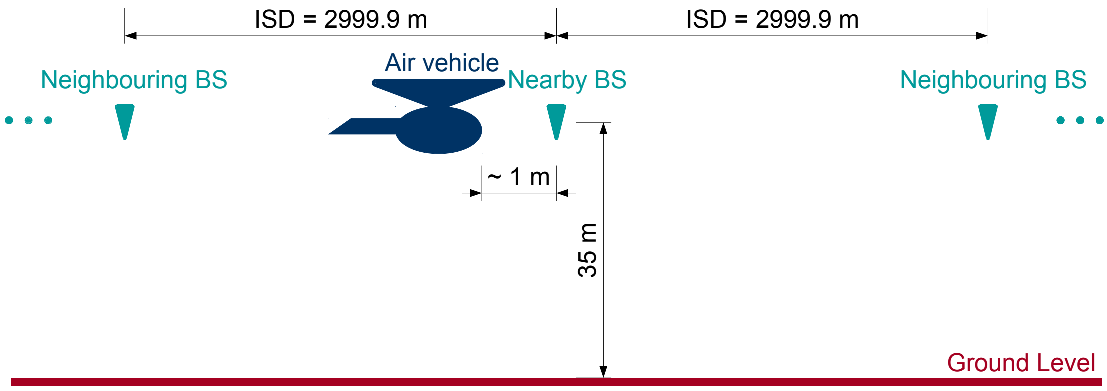


Figure 28 Geometrical arrangement: IFS due to nearby base station: 108.5 V/m, ISD = 2999.9 m. $TAAF_{VA,NA}$ due to neighbouring base stations (Σ_{NBS} = 324) up to the radio horizon (24.4 km): 0.1854 V/m

3.2.3 User equipment scenario (vector and network architecture approach):

This approach is not meaningful for user equipment, due to the fact that the frequency usage of these devices is not strategically planned, in contrast to base station network architectures.

3.3 Path loss model and statistical approach

Due to the fact, that the field accumulation quantities for the dense urban and the rural base station scenario are nearby negligible as soon as the vector and the network architecture approach are used, this approach is applied to the user equipment scenario only. Taking into account practical path loss models (PLM) we can assume that the power density of base stations in a certain distance of the EMI culprit will be increased by a factor of $1/r^4$ instead of $1/r^2$. This is due to blocking obstacles, in-house use, etc. Thus the additional field strength will decrease with the distance squared:

$$E_{\mathrm{Add\_}n,\mathrm{VA,PLM}} = \frac{\mathrm{IFS}}{(n \cdot \mathrm{ISD})^2} \cdot \sqrt{6 \cdot (n+1)}. \tag{40}$$

And also the applicable formula for the calculation of the additional field strength changes to

$$\mathrm{TAAF}_{\mathrm{VA,PLM}} = \sqrt{\sum_{n=1}^{m} E^2_{Add\_n,\mathrm{VA,PLM}}} = \frac{\mathrm{IFS}}{\mathrm{ISD}^2} \cdot \sqrt{\sum_{n=1}^{m} \frac{6 \cdot (n+1)}{n^4}} \tag{41}$$

where the upper sum limit *m* denotes the relation radio horizon radius over inter site distance.

In a second step one might assume statistics (ST) in a manner that only a certain fraction of the user equipments is operating at the same time. If only 17% (1/6) of the equipments are transmitting at the same time, the field strength are reduced to

$$E_{\mathrm{Add\_}n,\mathrm{VA,PLM,ST}} = \frac{\mathrm{IFS}}{(n \cdot \mathrm{ISD})^2} \cdot \sqrt{1 \cdot (n+1)}. \tag{42}$$

And also the applicable formula for the calculation of the additional field strength changes to

$$\mathrm{TAAF}_{\mathrm{VA,PLM,ST}} = \sqrt{\sum_{n=1}^{m} E^2_{Add\_n,\mathrm{VA,PLM}}} = \frac{\mathrm{IFS}}{\mathrm{ISD}^2} \cdot \sqrt{\sum_{n=1}^{m} \frac{1 \cdot (n+1)}{n^4}} \tag{43}$$

where the upper sum limit *m* denotes the relation radio horizon radius over inter site distance.

3.3.1 User equipment scenario (vector and path loss model approach)

$$\mathrm{TAAF}_{\mathrm{VA,PLM}} = 11.541\,\frac{\mathrm{V}}{\mathrm{m}} \text{ and } \mathrm{ETF}_{\mathrm{VA,PLM}} = \sqrt{\mathrm{IFS}^2 + \mathrm{TAAF}^2_{\mathrm{VA,PLM}}} = 11.925\,\frac{\mathrm{V}}{\mathrm{m}}. \quad (44)$$

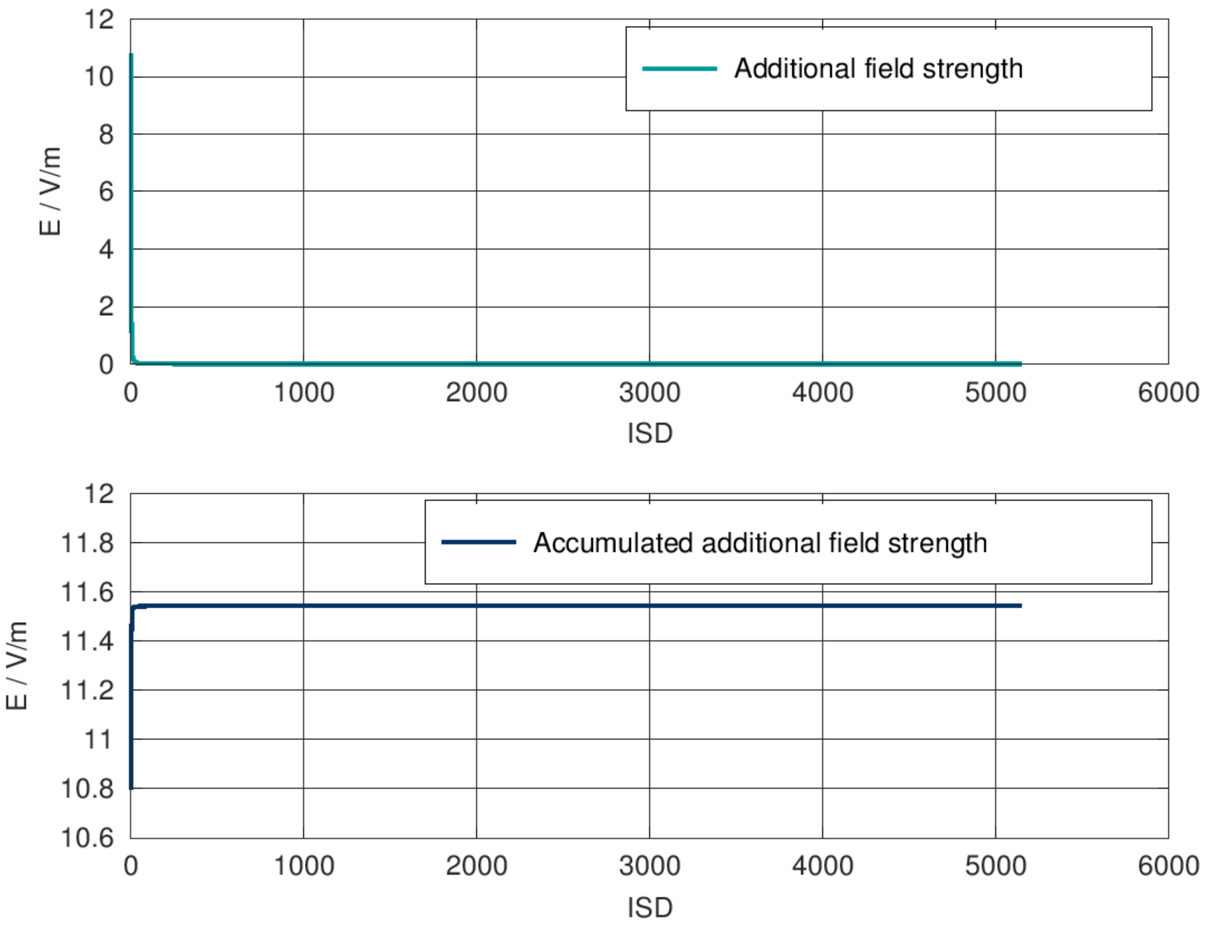


Figure 29 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring user equipments. The x-axis unit is given with multiples of distance radius between centre user equipment and neighbouring user equipments. Vector accumulation is used for field superposition. Additionally a path loss model approach is used. One ISD is equal to 0.981 m.

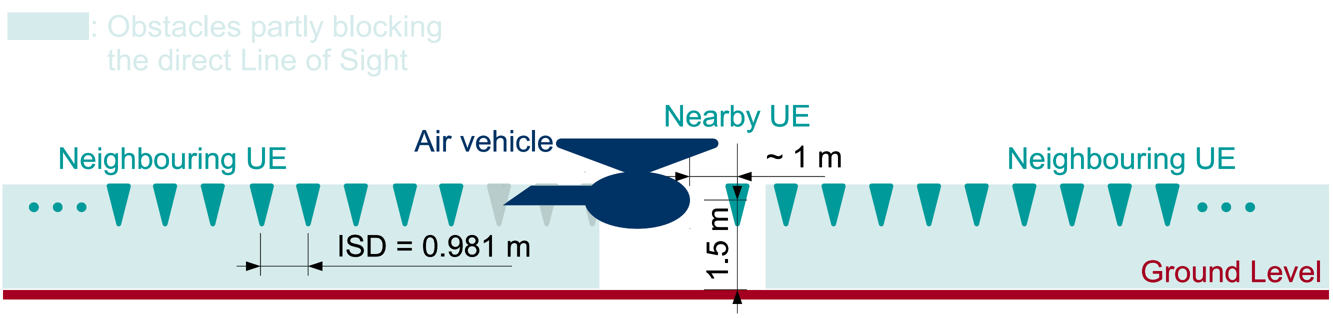


Figure 30 Geometrical arrangement: IFS due to nearby user equipment: 3 V/m, ISD = 0.981 m. $TAAF_{VA,PLM}$ due to neighbouring user equipments (Σ_{NUE} = 79.429·10^6) up to the radio horizon (5.045 km): 11.541 V/m

3.3.2 User equipment scenario (vector, path loss model and statistical approach)

$$\mathrm{TAAF}_{\mathrm{VA,PLM,ST}} = 4.712\frac{\mathrm{V}}{\mathrm{m}} \text{ and } \mathrm{ETF}_{\mathrm{VA,PLM,ST}} = \sqrt{\mathrm{IFS}^2 + \mathrm{TAAF}_{\mathrm{VA,PLM,ST}}^2} = 5.58\frac{\mathrm{V}}{\mathrm{m}}. \quad (45)$$

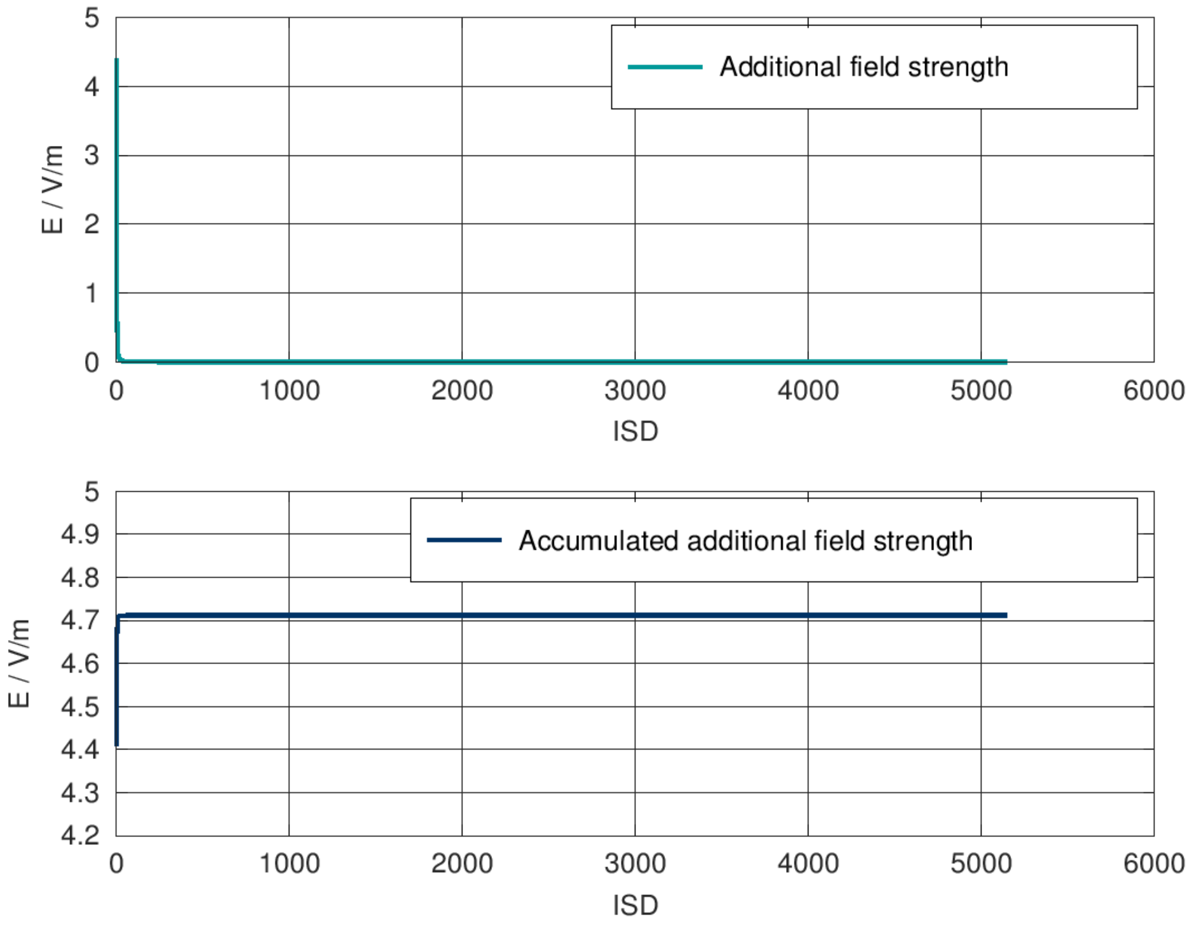


Figure 31 Individual contribution and integral behaviour of additional field strength at centre point due to neighbouring user equipments. The x-axis unit is given with multiples of distance radius between centre user equipment and neighbouring user equipments. Vector accumulation is used for field superposition. Additionally a path loss model approach is used and a statistic approach. One ISD is equal to 0.981 m.

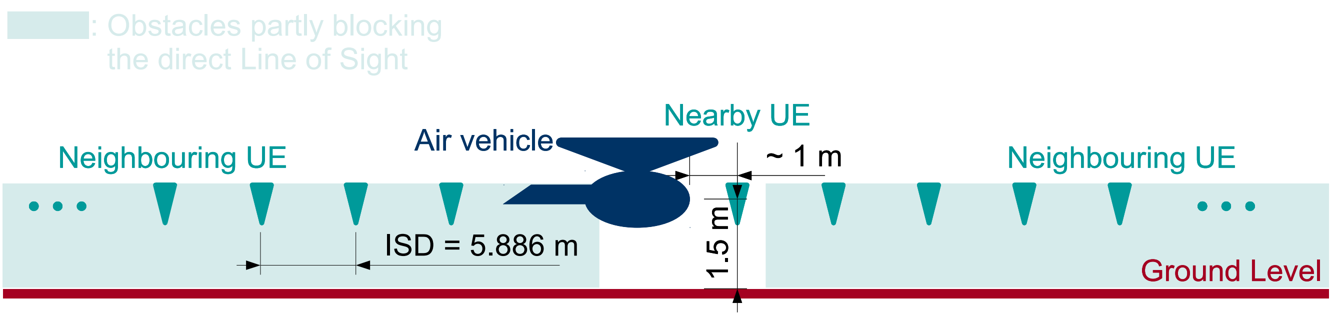


Figure 32 Geometrical arrangement: IFS due to nearby user equipment: 3 V/m, ISD = 5.886 m. $TAAF_{VA,PLM,ST}$ due to neighbouring user equipments ($\Sigma_{NUE} = 13.24 \cdot 10^6$) up to the radio horizon (5.045 km): 4.712 V/m

3.4 Field Accumulation – User equipment scenario 2

With this subchapter a second important scenario for the accumulated fields due to user equipments is investigated: Here it is assumed that the air vehicle is located in 25 m height. This increases the horizon clearly to 20.6 km compared to the 5.045 km resulting from the original scenario given with subchapter 2.8. Now we have to consider a radius of 20.6 km and thus a number of layers equals to 20600 m / 0.981 m = 20999 times ISD. The resulting total amount of neighbouring UE (NUE) up to the "horizon" that have to be considered is now increasing to

$$\mathrm{NUE} = \sum_{n=1}^{20999} 6 \cdot (n+1) = 1323 \cdot 10^6 \tag{46}$$

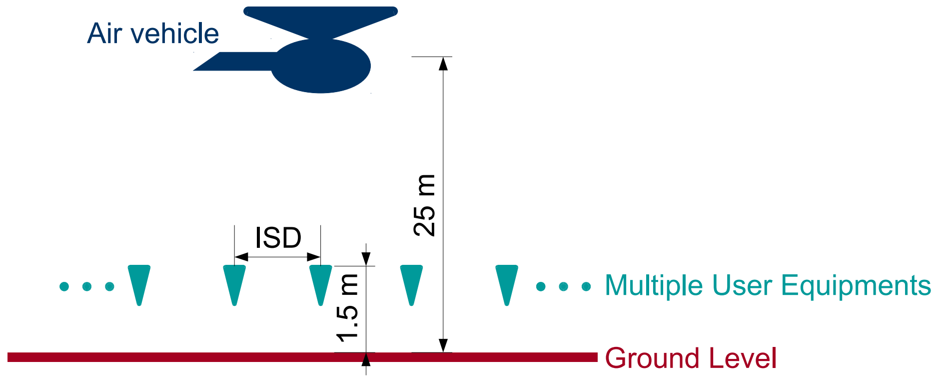


Figure 33 User equipment scenario 2, Geometrical arrangement: Air vehicle (EMI victim) 25 m above ground. IFS due to nearby user equipment: 0.13 V/m, ISD = 0.981 m.

The applicable formula to calculate the additional field strength is modified to take into account the geometrical situation shown with Figure 33. Total amount of additional field (TAAF) is now given by

$$\mathrm{TAAF} = \sum_{n=1}^{21407} 6 \cdot (n+1) \cdot \frac{\mathrm{IFS}}{\sqrt{(n \cdot \mathrm{ISD})^2 + 23.5^2}} = 385010\ \mathrm{V/m} \tag{47}$$

The additional amount due to the central user equipment directly underneath the air vehicle is given by 3 V/m / (25 – 1.5) = 0.13 V/m and hence can be neglected.

Making use of vector approach reduces the accumulated field strength to

$$\mathrm{TAAF_{VA}} = \mathrm{IFS} \cdot \sqrt{\sum_{n=1}^{21407} \frac{6 \cdot (n+1)}{(n \cdot \mathrm{ISD})^2 + 23.5^2}} = 19.59\ \mathrm{V/m}$$

Making use of vector approach and path loss model (*E~1/r*^{2}) reduces the accumulated field strength to

$$\mathrm{TAAF_{VA,PLM}} = \mathrm{IFS} \cdot \sqrt{\sum_{n=1}^{21407} \frac{6 \cdot (n+1)}{[(n \cdot \mathrm{ISD})^2 + 23.5^2]^2}} = 0.23\ \mathrm{V/m}$$

3.5 Field Accumulation – User equipment scenario 3

With this subchapter the previous scenario is varied in a manner that the air vehicles height was changed from 25 m to 10m. Thus the radio horizon is reduced from 20.6 km to 13.03 km, which means that less user equipments are “visible”. Nevertheless the geometrical distance between the air vehicle and certain user equipments is less in this reduced altitude.

The number of layers equals to 13029 m / 0.981 m = 13281 times ISD. The resulting total amount of neighbouring UE (NUE) up to the “horizon” that have to be considered is now given by

$$\mathrm{NUE} = \sum_{n=1}^{13029} 6 \cdot (n+1) = 529 \cdot 10^6 \tag{48}$$

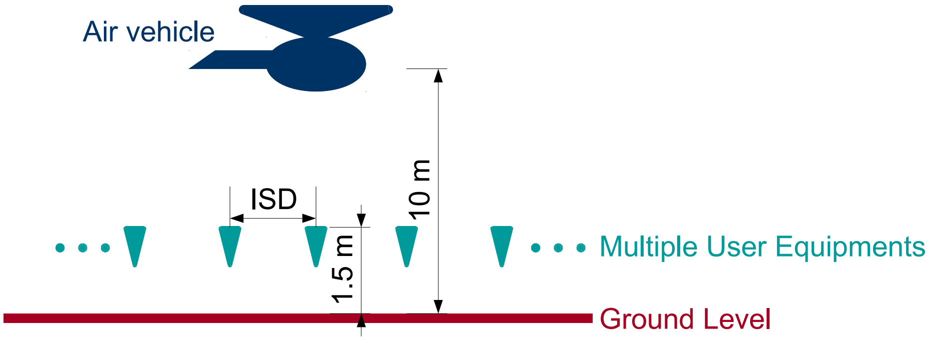


Figure 34 User equipment scenario 2, Geometrical arrangement: Air vehicle (EMI victim) 10 m above ground. IFS due to nearby user equipment: 0.35 V/m, ISD = 0.981 m.

The applicable formula to calculate the additional field strength is modified to take into account the geometrical situation shown with Figure (34). Total amount of additional field (TAAF) is now given by

$$\mathrm{TAAF} = \sum_{n=1}^{13029} 6 \cdot (n+1) \cdot \frac{\mathrm{IFS}}{\sqrt{(n \cdot \mathrm{ISD})^2 + 8.5^2}} = 243680\ \mathrm{V/m}. \tag{49}$$

The additional amount due to the central user equipment directly underneath the air vehicle is given by 3 V/m / (10 – 1.5) = 0.35 V/m and hence can be neglected.

Making use of vector approach reduces the accumulated field strength to

$$\mathrm{TAAF_{VA}} = \mathrm{IFS} \cdot \sqrt{\sum_{n=1}^{13252} \frac{6 \cdot (n+1)}{(n \cdot \mathrm{ISD})^2 + 23.5^2}} = 20.526\ \mathrm{V/m}.$$

Making use of vector approach and path loss model (*E~1/r*^{2}) reduces the accumulated field strength to

$$\mathrm{TAAF_{VA,PLM}} = \mathrm{IFS} \cdot \sqrt{\sum_{n=1}^{13252} \frac{6 \cdot (n+1)}{[(n \cdot \mathrm{ISD})^2 + 23.5^2]^2}} = 0.67\ \mathrm{V/m}$$

4 Conclusion

With this assessment paper the potential impact of newly introduced 5G infrastructure (Base Stations, BS) and devices (User Equipments, UE) on the electromagnetic environment for air vehicles is investigated. Special focus is the scenario where innovative air vehicles like VTOLS (air taxi) are operated in low altitude in a dense urban environment. Here multiple medium power BS and low power UE will transmit nearby, yielding an aggregated electromagnetic field threat. The quantification of this aggregated fields is investigated, the findings are as follows:

- Applying a very simple approach, making use of pure adding of the individual fields at the position of the air vehicle, yields aggregated field quantities of
    - ~ 263 V/m for dense urban environment, due to base stations
    - ~ 116 V/m for rural environments, due to base stations
    - ~ 94 kV/m, for dense urban environments due to user equipments (air vehicle altitude: 1.5 m)
    - ~ 385 kV/m, for dense urban environments due to user equipments (air vehicle altitude: 25 m)

It has to be emphasized that this very simple adding approach is improper and the values, especially for the user equipment scenarios (up to $1 \cdot 10^6$ devices / km^2), are not meaningful. A physically more realistic approach makes use of the assumption that the aggregated em fields are not strictly monochromatic and hence a vector approach for summarization is appropriate. Making use of this technique, the aggregated fields are reduced to:

- Field strength applying vector aggregation yields
    - ~ 62 V/m for dense urban environment, due to base stations
    - ~ 109 V/m for rural environments, due to base stations
    - ~ 25 V/m, for dense urban environments due to user equipments (air vehicle altitude: 1.5 m)
    - ~ 18 V/m, for dense urban environments due to user equipments (air vehicle altitude: 25 m)

One should relate this values to given HIRF environments of [1]:

Frequency	HIRF Environments		
	III, Rotorcraft Severe	I, Fixed Wing, Certification	II, Fixed Wing, Normal
	Field Strength (V/m), Average		
400 MHz – 700 MHz	200	50	40
700 MHz - 1 GHz	240	100	40
1 GHz - 2 GHz	250	200	160
2 GHz - 4 GHz	490	200	120
4 GHz - 6 GHz	400	200	160
6 GHz - 8 GHz	200 (170)	200	170
8 GHz - 12 GHz	330	300	230
12 GHz - 18 GHz	330	200	190
18 GHz - 40 GHz	420	200	150

Doing so ends in the finding, that the aggregated fields due to 5G user equipments are covered even by the less severe HIRF environment II (Fixed Wing, normal). The aggregated fields caused by base stations are covered if HIRF environment III (Rotorcraft, severe) is applied. Root cause for the high field strength values is not the field aggregation due to many base stations, but the possibility that the air vehicle approaches quite near to a single base station, which might transmit fields strength up to 61 V/m (dense urban) or even up to 108.5 V/m (rural). The additional aggregate fields of ~ 1 V/m (dense urban) or only 0.5 V/m (rural) of the neighbouring base stations can be neglected.

Further investigations were presented, taking into account additional practical rationales to calculate realistic aggregated field strength:

- For the base station scenarios (dense urban and rural) a network architecture approach is investigated, yielding an additional attenuation of the aggregated fields from
  - ~ 2 V/m to ~ 1 V/m for dense urban scenario and
  - ~ 0.34 V/m to ~ 0.18 V/m for the rural scenario.
- For the user equipment scenario an advanced path loss model approach is investigated, yielding an additional attenuation of the aggregated fields from
  - ~ 24.8 V/m to 11.5 V/m assuming that the air vehicles altitude is 1.5 m and
  - ~ 17.7 V/m to 0.23 V/m assuming that the air vehicles altitude is 25 m

Due to the fact, that the base stations scenario field strength are dominated by the quantity added from the nearby station and the user equipments entire field strength is pretty low anyway, these findings are mainly for informational purpose only.

Moreover the report provides empirical formulas allowing for quick recalculation of scenarios with modified parameters: E.g. if adjusted initial field strength IFS assumptions seem to be appropriate or if changed settings for the density (inter station distances ISD) of transmitters shall be checked. Also different altitudes of the EMI victim (air vehicle) can be investigated. For this purpose the radio horizon has to be recalculated and also the geometrical distance between air vehicle and transmitters has to be adjusted.

5 Bibliography

[1] EUROCAE ED-107A / SAE ARP5583A, 2010

[2] Balanis, C. A. “Advanced engineering electromagnetics”, John Wiley & Sons, 2008

[3] Rothammel, K. “Rothammels Antennenbuch” DARC Verlag, 2001

[4] Ellingson, W. S. “Radio Systems Engineering” Cambridge University Press, 2016

[5] Salous, S. “Radio Propagation Measurement and Chanel Modelling”, Wiley 2013

[6] Report ITU-R M.2412-0, 10/2017

[7] Report ITU-R M.2410-0, 11/2017

[8] Recommendation ITU-R M.2083-0, 09/2015

[9] ICNIRP GUIDELINES, “Guidelines for limiting exposure to time varying electric magnetic and electromagnetic fields (up to 300 GHz).

[10] Pawlak R, Krawiec P. and Zurek J., “On Measuring Electromagnetic Fields in 5G Technology”, IEEE 2019

[11] Novotny L. “Lecture Notes on Electromagnetic Fields and Waves”, ETH Zuerich, 2013