Consultancy Report

Non-ionizing Radiation Safety of Radio Base Stations

Rohde & Schwarz Hong Kong Limited
Units 105 – 107,1/F., Wireless Centre
Hong Kong Science Park, Shatin
New Territories, Hong Kong
Tel : +852 2264 3788
Fax : +852 2264 3699
www.rohde-schawarz.com

Hong Kong Applied Science and Technology Research Institute Company Limited
5/F, Photonics Centre, 2 Science Park East Avenue, Hong Kong Science Park, Shatin, Hong Kong
Tel : +852 3406 2800
Fax : +852 3406 2801
www.astri.org

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1.0	June 21, 2022	First version for publication.

List of Acronyms and Abbreviations

2G	Second Generation Mobile Network / Mobile Services
3G	Third Generation Mobile Network / Mobile Services
4G	Fourth Generation Mobile Network / Mobile Services
5G	Fifth Generation Mobile Network / Mobile Services
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
CA	Communications Authority of Hong Kong
CDF	Cumulative Distribution Function
EIRP	Effective Isotropic Radiated Power
EMF	Electromagnetic Field
ERP	Effective Radiated Power
FDD	Frequency Division Duplexing
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
mMIMO	Massive Multiple-Input-Multiple-Output Antenna
mmWave	Milli-meter Wave frequencies, i.e., frequencies above 24 GHz
MNO	Mobile Network Operator
NCRP	National Council on Radiation Protection and Measurements
NIR	Non-ionizing Radiation
OFCA	Office of the Communications Authority
Ofcom	Office of Communications
P-CPICH	Primary Common Pilot Channel
RBS	Radio Base Station
RSRP	Reference Signal Received Power
TDD	Time Division Duplexing
WHO	World Health Organization
Am^{-1}	Ampere Per Meter
D	Longest dimension of an antenna
dBi	Decibel Isotropic
E_{inc}	Incident Electric Field Strength
$E_{\mathrm{inc,RL}}$	Incident Electric Field Strength Reference Level
f	Frequency
GHz	Gigahertz
Hz	Hertz
H_{inc}	Incident Magnetic Field Strength
$H_{\mathrm{inc,RL}}$	Incident Magnetic Field Strength Reference Level
kHz	Kilohertz
m	Meter
MHz	Megahertz
S_{inc}	Incident Power Density
$S_{\mathrm{inc,RL}}$	Incident Power Density Reference Level
Sub-6 GHz	Frequencies below 6 GHz
Vm^{-1}	Volt Per Meter
W	Watt
Wm^{-2}	Watt Per Square Meter

Z_0	Impedance of Free Space equal to $120\pi\ \Omega$
θ	Azimuth angle
λ	Wavelength of an EMF
ϕ	Elevation angle
Ω	Ohm
$\max(a, b, \dots, z)$	The maximum value among a, b, …, z
$\min(a, b, \dots, z)$	The minimum value among a, b, …, z
$\sum_{a \in \mathcal{A}} S_a$	Summation of S_a for all values of a in the set $\mathcal{A}$
$\{S_n\}_{n=1}^{N}$	The set of values S_1, S_2, …, S_{N-1}, S_N
$\{S_a\}_{a \in \mathcal{A}}$	The set of S_a for all values of a in the set $\mathcal{A}$

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Executive Summary

As of 2022, mobile network operators ("MNOs") of Hong Kong have installed radio base stations ("RBSs") scattered throughout the territory to provide the Second Generation ("2G"), Third Generation ("3G"), Fourth Generation ("4G"), and Fifth Generation ("5G") mobile services. To enable the continuous development of mobile services in Hong Kong particularly in the 5G era and beyond, the Communications Authority ("CA") has adopted a number of facilitating measures, including the release of more spectrum to the mobile industry for provision of mobile services and introducing new schemes to facilitate RBS installations by MNOs. At the same time, supports of operation in the new spectrum bands and advanced radio technologies promised by 5G and the future generation mobile networks raised new considerations in respect of regulatory measures for controlling radiation safety of RBSs and the growing public concern in this regard. To address the technical matters and public concern in relation to radiation safety, in May 2021, the CA initiated a consultancy study on radiation safety of RBSs ("the Consultancy Study"). Rohde & Schwarz Hong Kong Limited was commissioned by the CA as the consultant and it partnered with Hong Kong Applied Science and Technology Research Institute Company Limited as a sub-consultant to undertake part of the Consultancy Study.

The objectives of the Consultancy Study were to advise the Office of the Communications Authority ("OFCA") on all technical matters in relation to non-ionizing radiation ("NIR") from RBSs and to assess the typical NIR exposure level of Hong Kong and recommend practical measures to ensure radiation safety of RBSs in line with the world's best practice. The Consultancy Study encompassed technical studies, technical exchanges with Hong Kong MNOs and RBS equipment vendors, theoretical analysis, computer simulations, and field measurements for investigating the various RBS deployment scenarios including RBSs

installed at roof top locations, at indoor locations, on street furniture (such as payphone kiosks, sheltered bus stops and lamp posts), and at external wall of buildings. It affirmed that the existing regulatory measures adopted by Hong Kong are aligned with internationally adopted guidelines on radiation safety, and the NIR levels in Hong Kong are generally low in the representative locations of public-accessible areas. The findings are summarized below in succinct and detailed in the body of this report:

- Hong Kong and many developed economies (such as Australia, New Zealand, the United Kingdom, Germany, Singapore, the United States, France, Japan, and Korea) adopt the safety limits or similar requirements of International Commission on Non-ionizing Radiation Protection ("ICNIRP") in their relevant regulatory measures for ensuring radiation safety of RBSs. NIR levels are generally expressed in terms of either incident power density or incident electric field strength for which these two formats are interconvertible. For ease of public understanding, it is recommended that NIR levels should be reported in terms of incident power density and percentage of the ICNIRP compliance level.

- The mechanisms for NIR measurements and monitoring by OFCA are on par with those of other regulatory bodies worldwide. To enhance Hong Kong public's awareness and confidence in NIR safety of RBSs, OFCA can publish with discretion NIR measurement results of public areas on a regular basis.

- NIR levels in public-accessible areas of Hong Kong are historically well below the ICNIRP safety limits. Based on OFCA's past records on street-level public-area measurements and measurements at the sampled households[1] in the vicinity of RBSs (i.e., household sites with potentially higher NIR level), at least 95% of the street-level public area measurements were below 5% of the ICNIRP compliance level and 95% of the measurements at the sampled households in the vicinity of RBSs were below 10% of the ICNIRP compliance level.

[1] Upon requests of the residents and with their consent for OFCA to conduct NIR measurements inside their households.

- Assessment models and computer simulation tools drawing reference to the relevant technical documents and recommendations issued by international organizations and standardization bodies were developed for evaluating NIR levels from RBSs with a view to supporting OFCA in exercising regulatory controls (such as assessing the feasibility of bringing new RBSs into operation, or adjusting the transmitting power of existing RBSs in the vicinity to ensure that the aggregate NIR level always be in compliance with the ICNIRP safety limit).

- Based on the researches, site surveys, and recommendations of Hong Kong MNOs, ten RBS deployment sites have been selected for NIR assessment and detailed studies. These selected sites were categorized as *Group A, Group B, Group C,* and *Group D*. *Group A* sites were selected for investigating the technical behaviors of RBSs that made use of massive multiple-input-multiple-output ("mMIMO") antennas. *Group B* sites were selected for verifying that the ICNIRP safety limits can continually be met even though the transmitting power of the RBSs were increased. *Group C* sites were selected for investigating NIR level with RBS antennas installed at different height and distances from the public-accessible areas. *Group D* sites were selected for investigating NIR level with multiple RBSs in the vicinity. Computer simulations and field measurements were conducted for investigation of NIR levels generated from the RBSs at these ten representative locations in Hong Kong. It is showed that the related NIR levels are found below 5% of the ICNIRP safety limits.

- mMIMO antenna is one of the key technologies promised by 5G and the future generations of mobile networks. Field measurement results showed that the time-averaged NIR level from RBSs that made use of mMIMO antennas with beamforming was within 1/8 to 1/5 of the worst case NIR level from the RBS due to the technical behaviors of mMIMO beamforming.

- A routine monitoring mechanism on NIR exposure in public-accessible areas in Hong Kong was proposed. It is recommended that OFCA should routinely monitor NIR levels in public-accessible areas by conducting NIR measurements regularly at appropriate locations (i.e., areas with higher density of RBSs in the vicinity, crowded areas with frequent public gathering or high pedestrian flow, etc.) and publish the measurement results on a regular basis for public consumption. At each measurement location, Broadband Measurements should be made for initial verification whether the NIR levels are sufficiently low, and Frequency-Specific Measurements should be made if there is a need to determine the dominant source(s) of NIR in the local areas. At the time of this study, automated NIR monitoring is not practically feasible as it requires setting up an extensive infrastructure that is costly to maintain or modify.

A pertinent part of the Consultancy Study was to assess whether there was any room to enhance the existing regulatory controls on emissions from RBSs. On one hand, using past NIR measurements to *extrapolate* NIR levels from RBSs based on Hong Kong's spectrum release plan for 2021 – 2023, it was identified that transmitting power of rooftop RBSs and RBSs installed at high heights on lamp posts could be increased while the NIR levels in public-accessible areas could be maintained on par with historically low levels. On the other hand, while transmitting power of RBSs installed on sheltered bus stops could also be increased, the total radiated power of all co-located RBSs (if any) should remain at low levels since these RBSs are typically deployed to support local hotspots. In other words, an MNO can install one or more RBS antennas on the same sheltered bus stop with different transmitting power for supporting its mobile services as long as the limit on the aggregated transmitting power can be met.

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1 Introduction

Radio base stations ("RBSs") are key functional units of a public mobile network. It is necessary for mobile network operators ("MNOs") to install RBSs scattered throughout the territory in order to provide uninterrupted communications services to support mobile phone calls and mobile Internet access, among others, to serve clients of the general public. RBSs transmit and receive signals conveyed by radio frequency electromagnetic field ("EMF"), and the level of EMF emitted from an RBS varies depending on the technologies adopted, the area that needs to be covered, distance of the users from the RBS, traffic on phone calls, the speed of data transmission, etc.

As of 2022, MNOs in Hong Kong provide the Second Generation ("2G"), Third Generation ("3G"), Fourth Generation ("4G"), and Fifth Generation ("5G") mobile services and their RBSs operate at frequencies ranging [2] from several hundred megahertz to tens of gigahertz. Compared with previous generations of mobile services, 5G could enable low-latency broadband connectivity, extraordinary high data speed and allow more devices for connection to the network at the same time. Such enhanced capabilities of 5G and future generations of mobile networks are realized using the conventional cellular design approach, i.e., by installing more RBSs with each RBS covering a smaller area, network access is thus shared among fewer users, and by deployment of more efficient massive multiple-input-multiple-output ("mMIMO") antenna technologies, and re-farmed/newly allocated frequency bands to mobile services in both sub-6 GHz frequency range (i.e., frequency bands below 6 GHz) and milli-meter wave ("mmWave") frequency range (i.e., frequency bands above 24 GHz). It is

[2] Annex A summarizes Hong Kong's spectrum release plan for 2021 – 2023 for the provision of public mobile services and wireless broadband services.

conceivable that, in the 5G era and beyond, there will be new RBS deployment scenarios with more deployment of mMIMO antennas[3] and operation at more new frequency bands.

1.1 New RBS Deployment Scenarios and the Proliferation of RBSs That Make Use of mMIMO Antennas in the 5G Era and Beyond

In Hong Kong, most existing RBSs (including 2G, 3G, 4G, and 5G networks) are deployed on rooftops, installed at external wall of buildings or mounted on walls, or on the ceiling in indoor environments. In the 5G era and beyond, it is envisioned that RBSs could be installed on street furniture[4] (such as payphone kiosks, sheltered bus stops, and lamp posts) as well. The various RBS deployment scenarios are illustrated in Figure 1-1. In general, rooftop RBSs and RBSs installed at external wall of buildings have relatively higher EMF emission levels in order to provide service coverage over large areas, whereas indoor RBSs have lower EMF emission levels to provide local service coverage. MNOs could also install RBSs on street furniture for enhancing outdoor service coverage. At a given location, it is possible that there are multiple RBSs in the vicinity deployed by more than one MNO which operate in multiple frequency bands using 2G, 3G, 4G, and/or 5G technologies.

mMIMO antenna is important for 5G and future generations of mobile networks. As shown in Figure 1-2, an RBS that makes use of conventional antenna (non-mMIMO) transmits radio signals uniformly within its entire coverage area, whereas an RBS that makes use of mMIMO antenna can concentrate radio signals, known as beamforming, in the directions towards the

[3] mMIMO antenna refers to an antenna that can form multiple directional beams for transmitting reference signals and data signals and a scheduling mechanism is adopted to use different beams with similar probability.

[4] See https://www.ofca.gov.hk/filemanager/ofca/en/content_757/traac6_2020.pdf.

targeted receivers[5]. It is conceivable that beamforming could enhance signal quality receivable by the targeted receivers, but at the same time it could increase the short-term EMF levels in some locations within the coverage area.

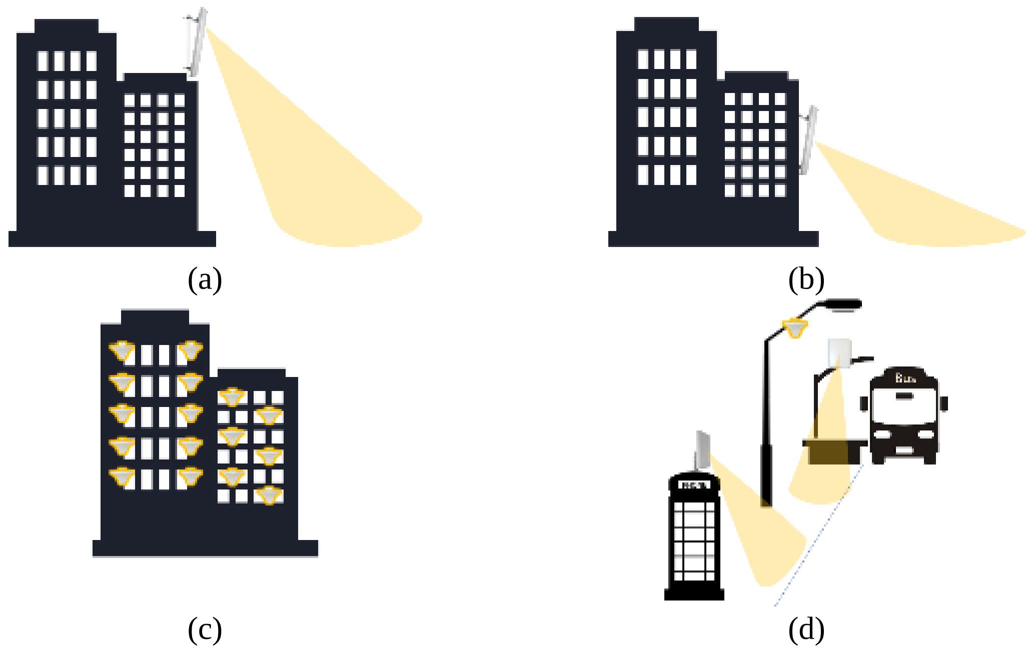

Figure 1-1: Illustration of RBS deployment scenarios.
(a) Rooftop RBSs. (b) RBS installed at external wall of buildings.
(c) Indoor RBSs. (d) RBSs installed on street furniture.

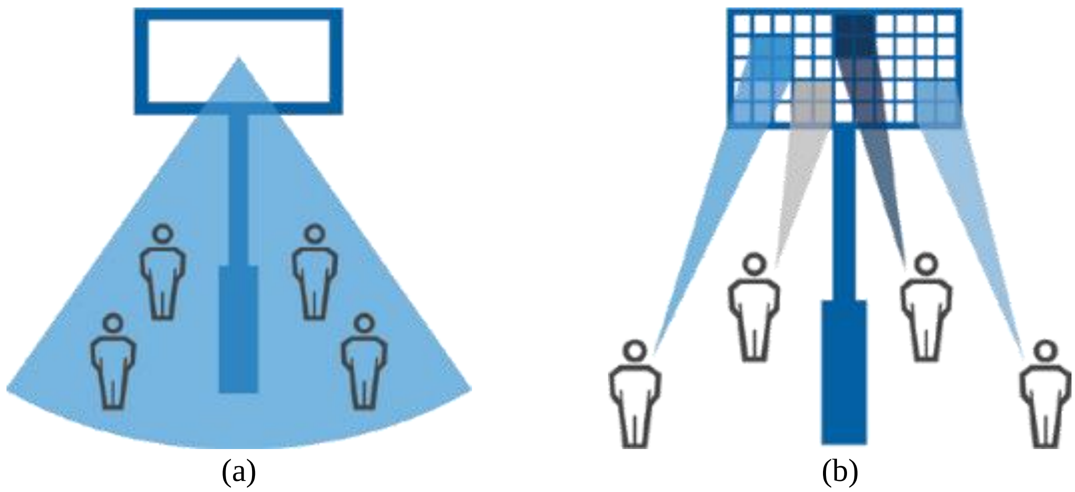

Figure 1-2: Comparison of the radiation patterns of (a) an RBS that makes use of conventional non-mMIMO antenna and (b) an RBS that makes use of mMIMO antenna.

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[5] See Annex D for an introduction on mMIMO antenna beamforming.

1.2 Regulatory Measures for Ensuring Radiation Safety of RBSs in the 5G Era and Beyond

Driven by the emergence of new RBS deployment scenarios as well as RBSs that make use of mMIMO antennas and operate at new frequency bands, there is a need to review and enhance the regulatory measures for monitoring with a view to ensuring the radiation safety of RBSs.

EMFs emitted by RBSs are classified as non-ionizing radiation[6] ("NIR"). Regarding safety standards of NIR exposure in human body, the World Health Organization ("WHO") recognizes the NIR safety limits set by the International Commission on Non-ionizing Radiation Protection ("ICNIRP") and encourages economies worldwide to adopt these limits. According to WHO, there is no sufficient scientific evidence indicating that exposure to NIR levels below the ICNIRP limits will cause adverse health effects. In this respect, many of the developed economies and economies with dense population (such as Australia, New Zealand, the United Kingdom, Germany, Singapore, the United States, France, Japan, and Korea) have adopted the ICNIRP safety limits or similar requirements in formulating their radiation safety standards. Based on the published information from these economies (see Section 3.3.3), NIR levels receivable in public-accessible areas are generally well below the ICNIRP safety limits.

In Hong Kong, the Communications Authority ("CA") also adopted the ICNIRP safety limits in establishing regulatory measures for monitoring and controlling radiation safety of RBSs[7].

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[6] There are two classes of radiation: ionizing radiation and NIR. NIR cannot cause harm by breaking chemical bonds in the human body. Examples of NIR commonly encountered in daily life are visible light, infrared rays, and radio broadcast signals. See https://emfguide.itu.int/emfguide.html, https://www.who.int/teams/environment-climate-change-and-health/radiation-and-health/non-ionizing/, https://www.fda.gov/radiation-emitting-products/cell-phones/radio-frequency-radiation-and-cell-phones, https://www.ofca.gov.hk/filemanager/ofca/Publicity/en/upload/10/2e.pdf, etc.

[7] Hong Kong media sometimes make reference to the recommendations for evaluating NIR safety published by the *Institute of Building Biology + Sustainability*. However, there is no publicly available records indicating that such recommendations are recognized by WHO or any major economy.

With the implementation of the said regulatory measures, NIR levels receivable in public-accessible areas in Hong Kong have been controlled well below the ICNIRP safety limits (see Section 7.1). In the 5G era and beyond, any new regulatory measures to be introduced would need to ensure that NIR levels in the public-accessible areas in Hong Kong will continue to be maintained at a safe level in compliance with international standards, while facilitating the introduction of new RBS deployment scenarios and advance technologies by MNOs. Specifically, to accommodate new RBS deployment scenarios, the Office of the Communications Authority ("OFCA") acting for the CA, should assess with a view to controlling NIR generated by multiple RBSs, from 2G to 5G, in the vicinity operating in multiple frequency bands in both sub-6 GHz and mmWave frequency ranges to ensure radiation safety. Moreover, to accommodate 5G RBSs (as well as future generations of RBSs) with more use of mMIMO antennas, OFCA should also take into consideration that NIR generated by mMIMO antenna varies with time due to beamforming operations.

1.3 Objectives and Organization of this Study Report

This report aims at exploring key technical matters in relation to NIR from RBSs, assessing the typical NIR exposure level of Hong Kong, and providing recommendations on practical measures to ensure radiation safety of RBSs in Hong Kong. The scope of this report include:

- To conduct research on the practices adopted by the leading overseas economies on their regulatory measures for controlling NIR generated by RBSs;
- To review the existing regulatory measures in Hong Kong having regard to the practices adopted in other jurisdictions and advise on practical new measures to ensure radiation safety of RBSs;

- To conduct studies in respect of NIR safety due to the use of new spectrum bands and radio technologies by 5G and future generation mobile networks, in particular the use of mmWave frequency bands and mMIMO antennas;

- To conduct computer simulations and field measurements and give an assessment on the public's exposure on NIR in Hong Kong as generated by RBSs of 2G to 5G mobile networks;

- To develop assessment models for evaluating NIR levels from RBSs to support OFCA in exercising regulatory controls; and

- To explore and propose practical routine monitoring mechanism on NIR in public-accessible areas in Hong Kong.

This report is divided into the following sections:

- Section 2 provides an overview on the ICNIRP EMF guidelines with emphasis on how they are applied for ensuring NIR safety of RBSs, and discusses the methodologies for assessing the allowable transmitting power levels of RBSs;

- Section 3 discusses the considerations for assessing the EMF emission levels for different RBS deployment scenarios and assesses the regulatory measures on NIR safety of RBSs adopted by Hong Kong drawing comparisons with the regulatory measures adopted by some overseas economies and proposing recommendations for enhancing the regulatory measures for ensuring NIR safety of RBSs.

- Section 4 summarizes the technical exchanges with Hong Kong MNOs regarding their RBS deployment strategies in the 5G era and beyond and with RBS equipment vendors regarding their RBS technical specifications;

- Section 5 presents the proposed assessment models for evaluating NIR levels from RBSs to support OFCA in exercising regulatory controls (such as assessing the feasibility of bringing new RBSs into operation, or adjusting the transmitting power of existing RBSs in the vicinity to ensure that the aggregate NIR level always be in compliance with the ICNIRP safety limit);

- Section 6 presents the computer simulation results and field measurement results on the NIR levels from RBSs in representative locations of Hong Kong;

- Section 7 presents the NIR measurement statistics of Hong Kong for illustrating the historical NIR levels in public-accessible areas and the predicted NIR levels in 2022 and beyond with a view to offering recommendations for enhancing the control of emissions of RBSs under different deployment scenarios;

- Section 8 presents the proposed routine monitoring mechanism on NIR in public-accessible areas in Hong Kong; and

- Section 9 sums up the findings of this study.

Aside from these sections, Annex A to Annex J provide quantitative information addressing other aspects of NIR analysis and RBS technical behaviors as part of this study report.

2 NIR Safety Limits for RBSs and Methodologies for Assessing the Allowable Transmit Power Levels of RBSs

In this section, an overview of the ICNIRP EMF guidelines is first provided with emphasis on how they should be applied for ensuring NIR safety of RBSs. After establishing the key concepts on NIR safety, the methodologies for assessing the allowable transmitting power levels of RBSs are discussed drawing references to the relevant findings of the various standardization bodies and regulatory bodies.

2.1 Overview on ICNIRP EMF Guidelines and Their Applications on Radiation Safety of RBSs

The ICNIRP EMF guidelines ("ICNIRP guidelines") specify quantitative reference levels for protection of humans from exposure to EMFs in the frequency range from 100 kHz to 300 GHz **[Ref 1]** which are classified as NIR. According to the ICNIRP guidelines, EMFs emitted from RBSs can lead to whole-body NIR exposure under which the main effect on the human body is to cause the body temperature to rise, and there is extensive evidence that the amount of heat so generated is not sufficient to cause harm for exposure to low NIR levels within the ICNIRP reference levels[8]. Specifically, the NIR level at a location can be characterized by incident power density S_{inc} in Wm^{-2}, incident electric field strength E_{inc} in Vm^{-1}, and incident magnetic field strength H_{inc} in Am^{-1}. For compliant with the ICNIRP guidelines, human exposure to NIR level (i.e., S_{inc}, E_{inc}, and H_{inc}) at a location as averaged over a 30-minute interval[9] should be within the corresponding frequency-specific whole-body average reference

[8] See https://www.icnirp.org/en/applications/base-stations/index.html and https://www.who.int/teams/environment-climate-change-and-health/radiation-and-health/non-ionizing/base-stations-wireless-technologies/.

[9] See Section 2.1.2.1 for discussions on the similarities and differences between averaging times and measurement times when assessing the NIR safety of RBSs.

levels (i.e., $S_{\mathrm{inc,RL}}$, $E_{\mathrm{inc,RL}}$, and $H_{\mathrm{inc,RL}}$) as summarized in Table 2-1, and graphical representations of the reference levels are depicted in Figure 2-1. The ICNIRP guidelines differentiate occupationally-exposed individuals from members of the general public. Occupationally-exposed individuals are exposed to NIR associated with their occupational duties; they are trained to be aware of potential risks and to employ appropriate harm-mitigation measures. Members of the general public may have no knowledge of or control over their exposure to NIR. Against this background, ICNIRP set different reference levels for exposure to NIR for occupationally-exposed individuals and the general public.

As shown in Table 2-1, some reference levels are *not applicable* for some frequency ranges because the corresponding parameters (i.e., S_{inc}, E_{inc}, or H_{inc}) do not need to be taken into account when demonstrating compliance with the ICNIRP guidelines[10].

Table 2-1: ICNIRP whole-body average reference levels for NIR exposure averaged over a 30-minute interval.

Exposure Scenario	**Frequency Range**	**Reference Levels (expressed as root mean square values)**			**RBS Frequency Band**
		Incident Electric Field Strength $E_{\mathrm{inc,RL}}(\mathrm{Vm^{-1}})$	**Incident Magnetic Field Strength** $H_{\mathrm{inc,RL}}(\mathrm{Am^{-1}})$	**Incident Power Density** $S_{\mathrm{inc,RL}}(\mathrm{Wm^{-2}})$	
Occupational	0.1 ≤ f ≤ 30 MHz	$660/f^{0.7}$	$4.9/f$	N/A	No
	30 < f ≤ 400 MHz	61	0.16	10	No
	400 < f ≤ 2000 MHz	$3f^{0.5}$	$0.008f^{0.5}$	$f\ \ /40$	Yes
	2 < f ≤ 300 GHz	N/A	N/A	50	Yes
General Public	0.1 ≤ f ≤ 30 MHz	$300/f^{0.7}$	$2.2/f$	N/A	No
	30 < f ≤ 400 MHz	27.7	0.073	2	No
	400 < f ≤ 2000 MHz	$1.375f^{0.5}$	$0.0037f^{0.5}$	$f\ \ /200$	Yes
	2 < f ≤ 300 GHz	N/A	N/A	10	Yes

10 See Section 2.1.2.3 for discussions on the similarities and differences between the ICNIRP 2020 guidelines and legacy ICNIRP 1998 guidelines.

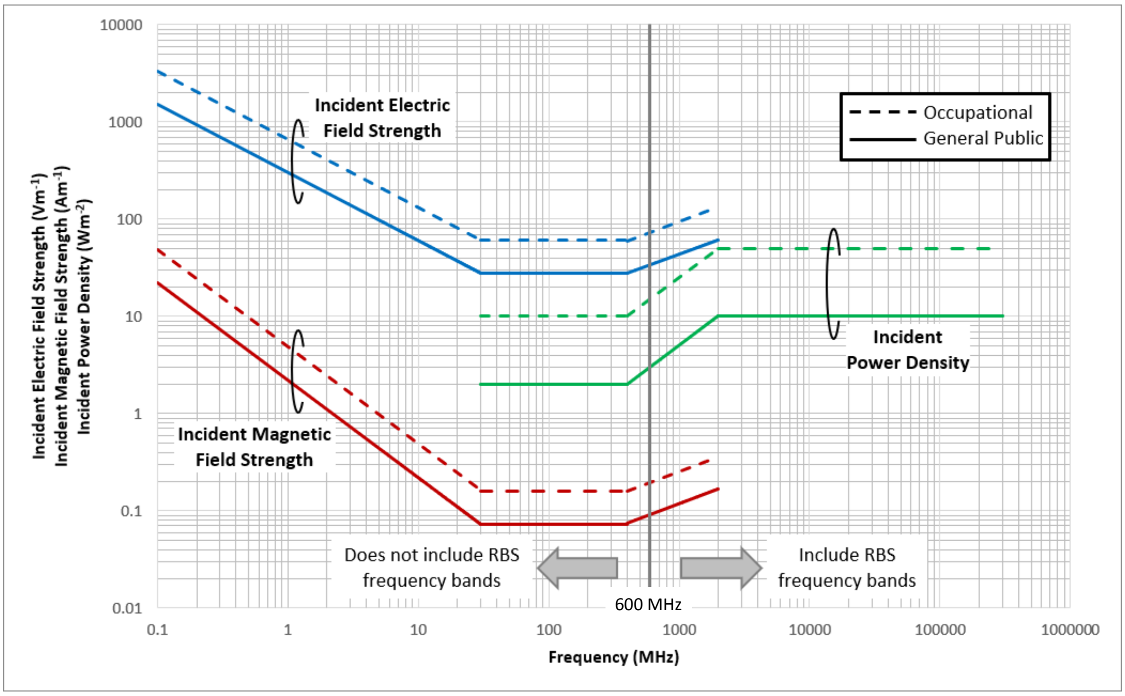

Figure 2-1: Graphical representations of ICNIRP whole-body average reference levels for NIR exposure averaged over a 30-minute interval.

2.1.1 Application of the ICNIRP Guidelines for Ensuring NIR safety of RBSs

2.1.1.1 EMF Field Regions and the Implications on Demonstrating Compliance With the ICNIRP Guidelines

EMFs exhibit different characteristics within the different *field regions* at different distances from the source antenna. Let λ denote the wavelength of an EMF and D the longest dimension of the EMF source antenna[11]. According to the ICNIRP guidelines, as illustrated in Figure 2-2, the *reactive near-field zone* is the region within $\lambda/2\pi$ meters from the antenna, the *radiative near-field zone* is the region between $\lambda/2\pi$ meters and $2D^2/\lambda$ meters from the antenna, and the *far-field zone* in the region beyond $2D^2/\lambda$ meters from the antenna. Within each field region, the necessary conditions for applying NIR reference levels to demonstrate compliance with the ICNIRP guidelines are summarized in Table 2-2.

[11] Annex B lists the dimensions of antennas typically used in different RBS deployment scenarios in Hong Kong in 2022.

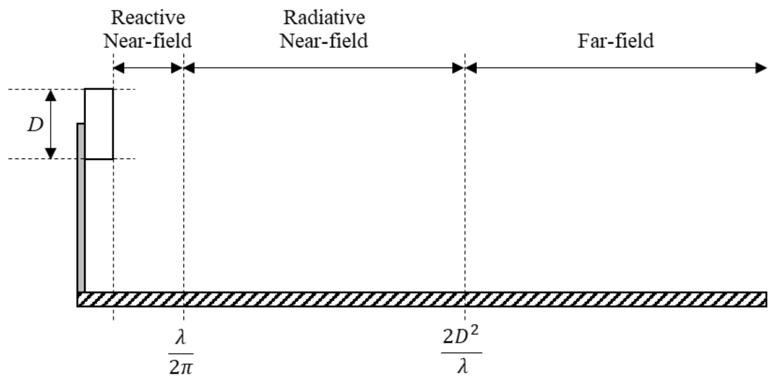

Figure 2-2: Illustration of EMF field regions.

In the far-field zone, S_{inc}, E_{inc}, and H_{inc} are related according to **[Ref 2]**

$$S_{\text{inc}} = \frac{\left(E_{\text{inc}}\right)^2}{Z_0} \text{ and } S_{\text{inc}} = Z_0 \left(H_{\text{inc}}\right)^2 , \quad (2\text{-}1)$$

where λ is the wavelength of the EMF, and $Z_0 = 120\pi\ \Omega = 377\ \Omega$ is the impedance of free space. When the conditions for equation (2-1) are satisfied, NIR level at a location can be characterized by either $S_{\text{inc,RL}}$, $E_{\text{inc,RL}}$, or $H_{\text{inc,RL}}$ since these parameters can be interconvertible.

As shown in Table 2-2, at the frequency range from 600 MHz to 43.5 GHz where 2G to 5G RBSs[12] operate, occupationally-exposed individuals and the general public are highly likely to only be exposed in the far-field zone or radiative near-field zone of EMFs emitted from RBSs (i.e., from a few centimeters away from the RBS antenna to and beyond the outer boundary of the reactive-near field zone). In this connection, it is sufficient to assess NIR safety of RBSs

[12] Annex A summarizes Hong Kong's spectrum release plan for 2021 – 2023 for the provision of public mobile services and wireless broadband services.

in terms of incident power density S_{inc} and compliance with the ICNIRP guidelines can be demonstrated if[13] $S_{\mathrm{inc}} \leq S_{\mathrm{inc,RL}}$.

Table 2-2: Necessary conditions for applying NIR reference levels to demonstrate compliance with the ICNIRP guidelines.

EMF Frequency Range	Necessary Conditions for Applying NIR Reference Levels to Demonstrate Compliance With the ICNIRP Guidelines			RBS Frequency Band
	Reactive Near-field Zone	Radiative Near-field Zone	Far-field Zone	
100 kHz < $f \leq$ 30 MHz	Requirements: $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$ and $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$ Zone outer boundary: Up to 477m from antenna	Requirements: $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$ and $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$	Requirements: $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$ and $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$	No
30 MHz < $f \leq$ 600 MHz	Requirements: $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$ and $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$ Zone outer boundary: Up to 1.59m from antenna	Requirements: either 1. $S_{\mathrm{inc}} \leq S_{\mathrm{inc,RL}}$; or 2. $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$ and $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$	Requirements: either 1. $S_{\mathrm{inc}} \leq S_{\mathrm{inc,RL}}$; 2. $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$; or 3. $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$	No
600 MHz < $f \leq$ 2 GHz	Requirements: $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$ and $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$ Zone outer boundary: Up to 0.08m from antenna	Requirements: either 1. $S_{\mathrm{inc}} \leq S_{\mathrm{inc,RL}}$; or 2. $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$ and $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$	Requirements: either 1. $S_{\mathrm{inc}} \leq S_{\mathrm{inc,RL}}$; 2. $E_{\mathrm{inc}} \leq E_{\mathrm{inc,RL}}$; or 3. $H_{\mathrm{inc}} \leq H_{\mathrm{inc,RL}}$	Yes
2 GHz < $f \leq$ 300 GHz	Requirements: NIR reference levels cannot be used to demonstrate compliance with the ICNIRP guidelines Zone outer boundary: Up to 0.02m from antenna	Requirements: $S_{\mathrm{inc}} \leq S_{\mathrm{inc,RL}}$	Requirements: $S_{\mathrm{inc}} \leq S_{\mathrm{inc,RL}}$	Yes

[13] Section 2.2 presents analytical models for the incident power density at different distances from the RBS antenna within different field regions.

2.1.1.2 The Presence of Multiple EMFs of Different Frequencies and the Implications on Compliance With the ICNIRP Guidelines

In practice, most areas are exposed to multiple EMF sources including RBS antennas that emit EMFs of multiple frequencies as well as EMF generated from other radiocommunications systems. According to the ICNIRP guidelines, when assessing whole-body NIR exposure in the presence of multiple EMFs, practical application of the reference levels (see Table 2-1) and compliance requirements (see Table 2-2) can be achieved by evaluating whether the following condition is satisfied:

$$\begin{aligned}\text{Compliance Level} = &\sum_{\substack{w\in\text{EMFs in}\\(0.1\leq f\leq 30\text{ MHz})}} \left\{\left(\frac{E_{\text{inc},w}}{E_{\text{inc,RL},w}}\right)^2 + \left(\frac{H_{\text{inc},w}}{H_{\text{inc,RL},w}}\right)^2\right\} \\ &+ \sum_{\substack{x\in\text{EMFs in}\\(30\text{ MHz}< f\leq 2\text{ GHz})}} \max\left\{\left(\frac{E_{\text{inc},x}}{E_{\text{inc,RL},x}}\right)^2, \left(\frac{H_{\text{inc},x}}{H_{\text{inc,RL},x}}\right)^2, \frac{S_{\text{inc},x}}{S_{\text{inc,RL},x}}\right\} \\ &+ \sum_{\substack{y\in\text{EMFs in}\\(2\text{ GHz}< f\leq 300\text{ GHz})}} \frac{S_{\text{inc},y}}{S_{\text{inc,RL},y}} \\ &\leq 1.\end{aligned} \qquad (2\text{-}2)$$

Equation (2-2) implies that each EMF source from a particular frequency range shall be below the respective reference level, and the aggregate effect of all EMFs be within the whole-body NIR exposure limits. Since NIR level in a particular environment could evolve over time with new EMF sources being put into service and legacy EMF sources being put out of operation, the NIR level at a location should be monitored on a regular basis and re-assessed whenever new EMF sources, in particular that emit high levels of EMFs, are deployed nearby. As discussed in Section 2.1.1.1, in assessing NIR safety of RBSs[14] that operate at the frequency range from 600 MHz to 43.5 GHz, equation (2-2) can be simplified as

$$\text{Compliance Level} = \sum_{\substack{y \in \text{EMFs emitted by RBSs in} \\ (600\ \text{MHz} < f \leq 43.5\ \text{GHz})}} \frac{S_{\text{inc},y}}{S_{\text{inc,RL},y}} \leq (1-\alpha) \tag{2-3}$$

where $0 \leq \alpha < 1$ is a margin[15] to 1) accommodate NIR level attributed by other radiocommunications systems nearby, and 2) ensure compliance with the ICNIRP guidelines even though new RBSs (that operate at the same or other frequency bands) are deployed in the future. Table 2-3 summarizes the NIR reference levels in frequency bands allocated to mobile services.

Equation (2-3) requires that the frequency-specific NIR level for each mobile services frequency band be precisely determined, which is not always practically feasible. Indeed, measurements of NIR level associated with a particular frequency band require specialized equipment and measurement set up. Instead, the compliance condition could be simplified by comparing the broadband NIR level against the most stringent reference level as follows:

[14] Annex A summarizes Hong Kong's spectrum release plan for 2021 – 2023 for the provision of public mobile services and wireless broadband services.

[15] Considerations for assessing the EMF emission levels for different RBS deployment scenarios are discussed in Section 3.1. The NIR margin should be designed considering holistically the number of RBSs to be deployed in the area, the frequency band used by each RBS, the coverage of each RBS, the distance to public-accessible areas, etc.

$$\text{Compliance Level} = \sum_{\substack{y \in \text{EMFs in} \\ (600\text{ MHz} < f \leq 43.5\text{ GHz})}} \frac{S_{\text{inc},y}}{S_{\text{inc,RL},y}} \leq \frac{\sum_{\substack{y \in \text{EMFs in} \\ (600\text{ MHz} < f \leq 43.5\text{ GHz})}} S_{\text{inc},y}}{\min\left\{\{S_{\text{inc,RL},y}\}_{\substack{y \in \text{EMFs in} \\ (600\text{ MHz} < f \leq 43.5\text{ GHz})}}\right\}} \leq 1. \quad (2\text{-}4)$$

As noted from equation (2-4), if the broadband NIR level, i.e., $\sum_{\substack{y \in \text{EMFs in} \\ (600\text{ MHz} < f \leq 43.5\text{ GHz})}} S_{\text{inc},y}$, is below the most stringent reference level, the compliance level is always less than one, i.e., compliance with the ICNIRP limits. In general, it is *effective and efficient* to assess NIR safety of RBSs based on broadband NIR level when NIR levels are relatively low. However, the mobile service frequency bands cover a large frequency range and broadband NIR measurements (hereinafter referred to as "Broadband Measurements") could include NIR attributed by other radiocommunications systems nearby. For a high broadband NIR level, there is a need to determine which frequencies (attributed by RBSs or other systems) are the dominant sources of the NIR and it is not feasible to extract the frequency-specific NIR level from the broadband NIR level however. In summary, Broadband Measurements and frequency-specific NIR measurements (hereinafter referred to as "Frequency-specific Measurements") could both be used for assessing NIR safety of RBS[16]. Therefore, Broadband Measurements should be made for initial verification whether the NIR levels are sufficiently low, and Frequency-specific Measurements should be made if there is a need to determine the dominant source(s) of NIR.

[16] Equipment and methodologies for making Broadband Measurements and Frequency-specific Measurements are presented in Section 6.3.

Table 2-3: Incident electric field strength reference levels, incident magnetic field strength reference levels, and incident power density reference levels for members of the general public for different mobile services frequency bands.

Frequency Band	Incident Electric Field Strength Reference Level $E_{\mathrm{inc,RL}}(\mathrm{Vm}^{-1})$	Incident Magnetic Field Strength Reference Level $H_{\mathrm{inc,RL}}(\mathrm{Am}^{-1})$	Incident Power Density Reference Level $S_{\mathrm{inc,RL}}(\mathrm{Wm}^{-2})$
600 MHz	33.68	0.091	3
700 MHz	36.38	0.098	3.5
850 MHz	40.09	0.11	4.25
900 MHz	41.25	0.11	4.5
1800 MHz	58.34	0.16	9
2100 MHz to 43.5 GHz	61.50	0.17	10

2.1.2 Additional Considerations When Applying the ICNIRP Guidelines

2.1.2.1 NIR Level Measurement Time

The ICNIRP reference levels (see Table 2-1) or safety limits are defined as the limits for human exposure to NIR at a location averaged over a 30-minute interval. According to the ICNIRP guidelines, such a 30-minute interval is the amount of time taken for body temperature to rise under whole-body NIR exposure. However, the averaging time is not necessarily be the average measurement time used to estimate NIR level at a location. It is shown in **[Ref 3,** Appendix V**]** that NIR level at a location attributed by RBSs transmissions could be estimated over a 1-minute interval, which is sufficient for NIR measurements to converge to a level that reflects the *averaged effects* contributed by all nearby RBS emissions (e.g., average traffic load for all the RBSs over time).

2.1.2.2 Assessing NIR Level Based on RBS Reference Signals

As detailed in Annex D, NIR level at a location attributed to RBS transmissions could be affected by traffic load. Moreover, for RBSs that make use of mMIMO antennas, NIR level at a location could also be affected by the direction(s) of the transmitting beams due to mMIMO beamforming. As a result, NIR level measured at a location may not reflect the nominal or extreme conditions. According to **[Ref 2] [Ref 4]** and references therein, a *worst case* bound on the NIR level at a location could be extrapolated from the measured NIR level attributed by reference signals as broadcasted by RBSs periodically. In other words, during field measurements, in case the broadband NIR level is relatively high and there is a need to determine which RBSs are the dominant NIR sources, measurements of NIR level contributed by the RBS reference signals could be made. As long as NIR level measurement of the RBS reference signals is below the ICNIRP safety limits, the actual NIR level under extreme conditions should also be below the ICNIRP safety limits. Annex E presents the methodology and analytical model for estimating the total NIR level of a target RBS based on reference signal measurement.

2.1.2.3 Similarities and Differences Between the ICNIRP 1998 Guidelines and the ICNRIP 2020 Guidelines in Relation to NIR Safety of RBSs

The ICNIRP guidelines were first published as the ICNIRP 1998 guidelines **[Ref 5]** and they have been revised over the years based on newer studies. In relation to NIR safety of RBSs, the most recent ICNIRP 2020 guidelines **[Ref 1]** maintain the same reference levels[17] for NIR exposure (see Table 2-1) for mobile service frequency bands[18], i.e., in the frequency range from 600 MHz to 43.5 GHz. Therefore, even though many economies have established regulatory measures for controlling NIR generated by RBSs based on the ICNIRP 1998 guidelines, these measures continue to be applicable under the ICNIRP 2020 guidelines.

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[17] The ICNIRP 2020 guidelines only specify incident power density reference levels for the frequency range $2 < f \leq 300$ GHz, whereas the ICNIRP 1998 guidelines also specify *equivalent* incident electric field strength reference levels and incident magnetic field strength reference levels. For reference, Annex F lists the complete set of reference levels of the ICNIRP 2020 guidelines and the ICNIRP 1998 guidelines.

[18] Annex A summarizes Hong Kong’s spectrum release plan for 2021 – 2023 for the provision of public mobile services and wireless broadband services.

2.2 Methodologies for Modeling the EMF Emitted by an RBS Antenna and Determining the Maximum Allowable Transmit Power Levels of RBSs

As far as NIR safety of RBSs is considered, assessment of the public's NIR exposure level at a location is most accurately achieved through on-site measurements. However, on-site measurements may not be always practically feasible since 1) in the planning stage, MNOs have yet to install the new RBSs concerned, and 2) the regulatory bodies may need to assess *beforehand* the resulting NIR level after the planned RBSs are eventually brought into operation. Analytical methodologies are commonly used for predicting NIR levels based on the maximum allowable transmitting power of RBSs, and these models provide a means for MNOs to plan coverage areas, and for regulatory bodies to exercise control on the aggregate EMF emissions from RBSs in a location. Internationally, various standardization bodies and regulatory bodies have conducted research and published recommendations on methodologies for modeling EMF emissions from RBSs and assessing the allowable transmitting power levels of RBSs **[Ref 2] [Ref 4] [Ref 6] [Ref 7] [Ref 8] [Ref 9]**. The findings of these research works are summarized in the following paragraphs.

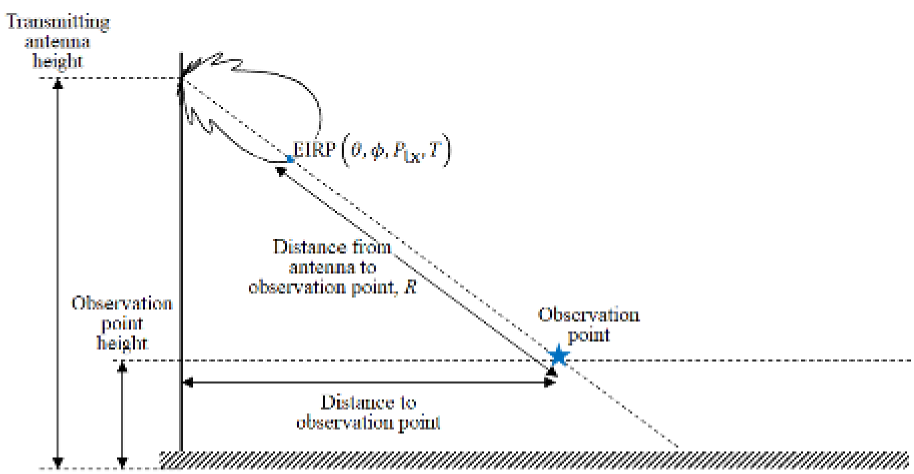

Figure 2-3: Illustration of scenario of estimating NIR level at an observation point.

Consider the scenario illustrated in Figure 2-3. Given an RBS with maximum transmitting power P_{tx}, let $\mathrm{EIRP}(\theta, \phi, P_{\mathrm{tx}}, T)$ denote the effective isotropic radiated power ("EIRP") towards azimuth angle θ and elevation angle ϕ, and averaged over time-interval *T*. The incident power density at an observation point *R* meters away from the RBS antenna can be approximated as

$$S_{\mathrm{inc}}(\theta, \phi, R, P_{\mathrm{tx}}, T) = \frac{\mathrm{EIRP}(\theta, \phi, P_{\mathrm{tx}}, T)}{4\pi R^2}. \tag{2-5}$$

For example, if public-accessible areas are $R = R_0$ meters from an RBS antenna and the incident power density shall be below a *target* incident power density limit $S_{\mathrm{inc,limit}}$, the maximum transmitting power $P_{\mathrm{tx}} = P_0$ of the RBS could be predicted from equation (2-5) such that $\frac{\mathrm{EIRP}(\theta,\phi,P_0,T)}{4\pi R_0^2} \leq S_{\mathrm{inc,limit}}$. Drawing reference to **[Ref 6]**, the time-averaged EIRP can be modelled as

$$\mathrm{EIRP}(\theta, \phi, P_{\mathrm{tx}}, T) = P_{\mathrm{tx}} F_{\mathrm{t2r}} F_{\mathrm{rdn}} B_{\mathrm{ant}}(\theta, \phi, T) G_{\mathrm{ant}}, \tag{2-6}$$

where[19]

1) G_{ant} is the maximum antenna gain in the main lobe of the radiation pattern;

2) $0 < B_{\mathrm{ant}}(\theta, \phi, T) \leq 1$ is a function modeling the normalized radiation pattern averaged over time *T*;

[19] In Annex D, a model is presented in equation (D-1) on the *short-term EIRP* of an RBS using different beams for transmitting reference signals and data signals. Equation (2-6) reflects the *long-term average EIRP* of an RBS using different beams for transmitting data signals under high traffic load (and the impacts of transmitting reference signals are negligible).

3) $0 < F_{\mathrm{rdn}} \leq 1$ is a power reduction factor to compensate for the time-averaged characteristics of mMIMO beamforming; and

4) $0 < F_{\mathrm{t2r}} \leq 1$ is a factor modeling the fraction of time the RBS is transmitting in relation to the transmit-receive duty cycle.

As elaborated in Annex D, conventional non-mMIMO antenna transmits radio signals using a fixed radiation pattern and so, with respect to equation (2-6), the maximum antenna gain G_{ant} and the time-averaged normalized radiation pattern $B_{\mathrm{ant}}(\theta, \phi, T)$ are equal to those of the fixed radiation pattern and the power reduction factor $F_{\mathrm{rdn}} = 1$. On the other hand, mMIMO antenna transmits radio signals using a dynamically-selected radiation pattern chosen in accordance with the vendor-specific algorithms. The number of radiation patterns supported by an mMIMO antenna and the technical specifications (e.g., gain, beamwidth, etc.) of its respective radiation patterns depend on the number of radiating elements built into the mMIMO antenna and subject to the vendor specific design. At the time of this study, there are no standardized approaches for determining $B_{\mathrm{ant}}(\theta, \phi, T)$ and F_{rdn}. In **[Ref 4] [Ref 8]**, it is shown that statistical analysis could be used to determine the power reduction factor F_{rdn}; however, this method is difficult to implement in practice as it has significant dependencies on the RBS technical behaviors as well as the RBS deployment scenario. Based on market researches and 5G RBS standard specifications available in 2022 as well as the field measurement results[20], an RBS generally uses radiation patterns with higher EIRP in the directions towards the targeted receivers and the upper bounds for G_{ant}, $B_{\mathrm{ant}}(\theta, \phi, T)$, and F_{rdn} could be determined as follows.

[20] Field measurement results are presented in Section 6.3.

Without loss of generality, it is assumed that an mMIMO antenna supports N *non-overlapping* radiation patterns (along the azimuth and elevation directions) with antenna gains $\{G_{\mathrm{ant},n}\}_{n=1}^{N}$, normalized radiation patterns $\{B_{\mathrm{ant},n}(\theta,\phi)\}_{n=1}^{N}$, $0 < B_{\mathrm{ant},n}(\theta,\phi) \leq 1$, and maximum average transmit power levels[21] $\{P_{\mathrm{tx},n}\}_{n=1}^{N}$, where $0 < P_{\mathrm{tx},n} \leq P_{\mathrm{tx}}$.

As illustrated in Figure 2-4, user terminals are generally randomly distributed within the RBS coverage area with equal probability and, in the extreme scenario, *all* non-overlapping radiation patterns could be used for transmission simultaneously such that[22]

- The time-averaged normalized radiation pattern is given by $B_{\mathrm{ant}}(\theta,\phi,T) = 1$;
- The maximum antenna gain is given by $G_{\mathrm{ant}} = \max\{G_{\mathrm{ant},n}\}_{n=1}^{N}$; and
- The power reduction factor is given by $F_{\mathrm{rdn}} = \max\left\{\frac{P_{\mathrm{tx},n}}{P_{\mathrm{tx}}}\right\}_{n=1}^{N}$.

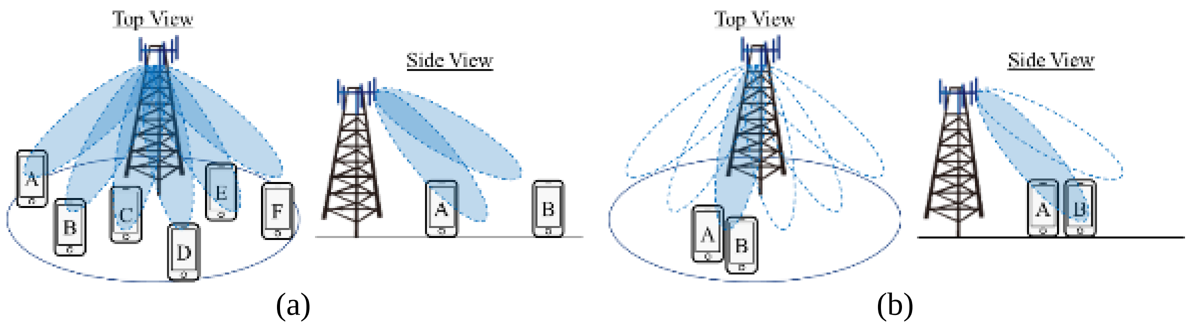

Figure 2-4: Illustration of mMIMO beamforming (a) when terminals are distributed throughout the RBS coverage area and (b) when terminals are concentrated at an area.

[21] Subject to the technical specifications and configurations of an RBS that makes use of mMIMO antenna, the maximum average transmission power level for each radiation pattern could be less than the maximum transmission power level (e.g., this is an implementation choice for maintaining the total transmission power level below the maximum level when multiple radiation patterns are used).

[22] Field measurement results that reflect a certain reproducible power reduction factor are presented in Section 6.3.2. Based on these observations, recommendations will be provided on whether there is any room to relax or tighten the existing regulatory controls on the emissions of RBSs.

The transmit-receive duty cycle of an RBS depends on the duplexing scheme for transmission and reception. Under frequency division duplexing ("FDD"), the RBS always transmits on a particular frequency band and so F_{t2r}=1. Under time division duplexing ("TDD"), the RBS alternately transmits and receives on a same frequency band, and F_{t2r} can be approximated by the downlink-to-uplink ratio. Table 2-4 summarizes the duplexing schemes used by 2G to 5G mobile networks in Hong Kong and the corresponding transmit-receive duty cycle factor.

Table 2-4: Summary of the duplexing schemes used by 2G to 5G mobile networks in Hong Kong and the corresponding transmit-receive duty cycle factor.

Mobile Service	Duplexing Scheme	Downlink-to-uplink Ratio	Transmit-receive Duty Cycle Factor F_{t2r}
2G	FDD	N/A	1
3G	FDD	N/A	1
4G	FDD	N/A	1
	TDD	3:1	0.75
5G	FDD	N/A	1
	TDD (sub-6 GHz frequency bands)	7:3	0.7
	TDD (mmWave frequency bands)	4:1	0.8

2.2.1 Trends of Incident Power Density at Different Distances and Directions From an RBS Antenna and the Implications on Compliance With the ICNIRP Guidelines

According to **[Ref 7]** and references therein, equation (2-5) is valid within the far-field zone of the EMF[23]. Moreover, as demonstrated in the computer simulation results provided in Annex C, the antenna gain in the radiative near-field zone of the EMF is generally lower than the expected antenna gain G_{ant}, and so equation (2-5) provides an *upper bound* for the incident power density within the radiative near-field zone of the EMF. It can be observed from equation (2-5) that the incident power density decreases with increasing distance R from the RBS antenna. If the incident power density at a location (e.g., $\theta = \theta_0$, $\phi = \phi_0$, $R = R_0$)

[23] See Section 2.1.1.1 for the definitions of EMF field regions.

attributed by the EMF emitted by an RBS antenna is compliant with the ICNIRP guidelines (i.e., $S_{\text{inc}}(\theta = \theta_0, \phi = \phi_0, R = R_0, P_{\text{tx}}, T) \leq S_{\text{inc,RL}}$), then the power density level at locations along the same direction further away from the RBS antenna are also compliant with the ICNIRP guidelines (i.e., $S_{\text{inc}}(\theta = \theta_0, \phi = \phi_0, R, P_{\text{tx}}, T) \leq S_{\text{inc,RL}}$ for $R > R_0$). For illustration, Figure 2-5 shows how the incident power density decreases with distance from the RBS antenna: Suppose EIPR of an RBS antenna is 100W, the incident power density is below 0.32Wm^{-2} beyond 5m away from the RBS antenna and well below the ICNIRP safety limits.

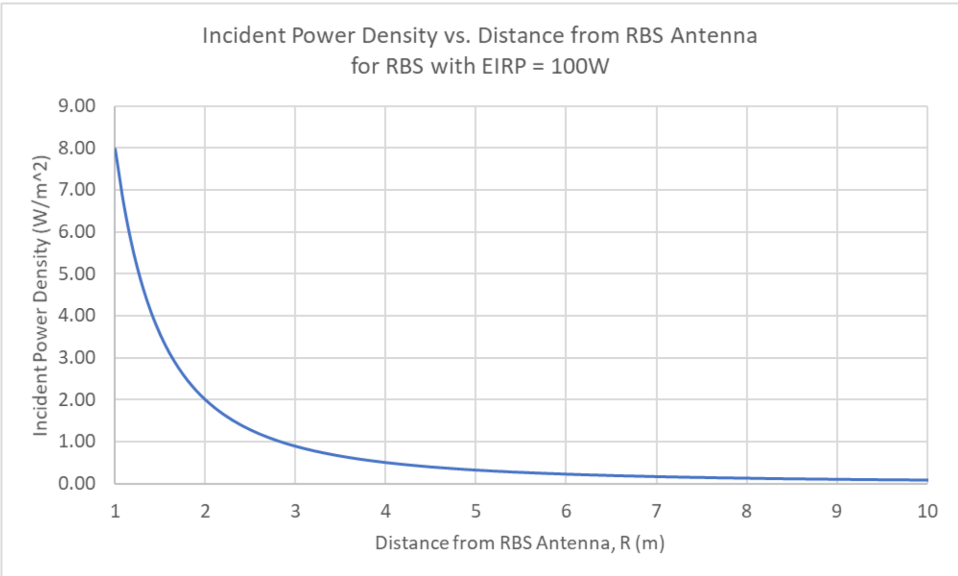

Figure 2-5: Illustration of how the incident power density decreases with distance from the RBS antenna.

3 Overview of Regulatory Measures on NIR Safety of RBSs Adopted by Hong Kong and Overseas Economies

In this section, the considerations for assessing the EMF emission levels for different RBS deployment scenarios are first discussed. After that, the regulatory measures on NIR safety of RBSs adopted by Hong Kong are presented in details followed by a discussion on the key similarities and differences with the regulatory measures adopted by some overseas economies. Drawing reference to some of the effective regulatory measures adopted by overseas economies, some recommendations are provided for enhancing the regulatory measures of Hong Kong on NIR safety of RBSs.

3.1 Considerations for Assessing the EMF Emission Levels for Different RBS Deployment Scenarios

MNOs deploy RBSs to provide service coverage as well as to enhance network capacity. When RBSs are deployed to provide service coverage, it is generally effective to deploy RBS antennas at higher altitudes with higher EMF emission levels so that radio signals can propagate over farther distances and penetrate through building obstacles to reach users. When RBSs are deployed to enhance network capacity by means of frequency reuse as illustrated in Figure 3-1, it is generally effective to deploy RBSs antennas at lower altitudes with lower EMF emission levels so as to better control the coverage area and reduce mutual interference with other co-frequency RBSs.

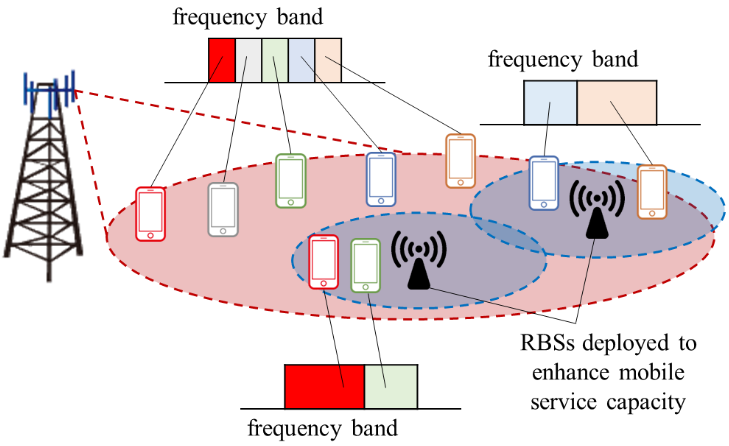

Figure 3-1: Illustration of RBSs deployed to enhance mobile service coverage by means of frequency reuse.

In the 5G era and beyond, RBSs could be deployed on rooftops, installed at external wall of buildings, mounted on walls or on the ceiling in indoor environments, or installed on street furniture (such as payphone kiosks, sheltered bus stops and lamp posts). MNOs can address different requirements using different RBS deployment scenarios (e.g., to patch coverage holes, to optimize signal strength or increase network capacity at an area to meet consumer demand, etc.) to address clients' needs.

In relation to NIR safety, as elaborated in Section 2.1, EMF emission levels for all RBS deployment scenarios should be regulated such that the NIR level is always in compliant with the ICNIRP guidelines at public-accessible areas (see Section 2.2.1 for discussions on the relationship between NIR level at a location and the distance from an RBS antenna). In the following, some considerations for assessing the EMF emission levels under different RBS deployment scenarios are discussed.

Rooftop RBSs

As illustrated in Figure 3-2, multiple MNOs may deploy their RBS antennas on the same rooftop site and provide mobile services using multiple frequency bands. At locations near the rooftop site, users will be exposed to aggregate NIR level due to EMF emissions from all the RBS antennas on the concerned rooftop site. As rooftop RBSs are separated from nearby pedestrian walkways by a long distance, NIR level at the pedestrian walkways is usually low. However, sometimes there is a short distance separation between rooftop RBSs and nearby buildings, and the NIR level could be relatively high at those buildings. The EMF emission levels of rooftop RBSs should be limited such that the NIR level at the nearest public-accessible areas are always compliant with the ICNIRP safety limits.

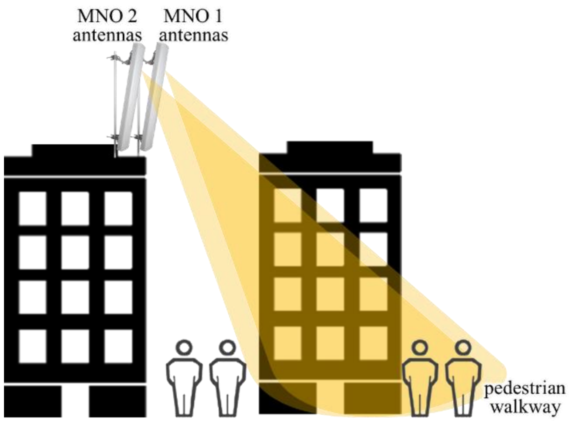

Figure 3-2: Illustration of RBSs deployed on rooftops.

RBSs installed on street furniture (such as payphone kiosks, sheltered bus stops and lamp posts)

As illustrated in Figure 3-3, RBSs installed on street furniture (such as sheltered bus stops and payphone kiosks) are in close proximity to pedestrian walkways and vehicles on the road, and there are more stringent considerations for the EMF emission levels from RBSs. Due to space constraint, there are restrictions on the number of MNOs sharing the same street furniture.

(a) (b)

Figure 3-3: Illustration of RBSs deployed on sheltered bus stops (a) Side view, (b) Front view.

As illustrated in Figure 3-4, RBSs installed on lamp posts could be placed at different heights above nearby pedestrian walkways and could even be in close proximity to nearby buildings. EMF emission levels of the RBSs should be limited such that the NIR level at the nearest public-accessible areas – at nearby pedestrian walkways or buildings – are always compliant with the ICNIRP guidelines. Same as street furniture, due to space constraint, there are restrictions on the number of MNOs sharing the same lamp post.

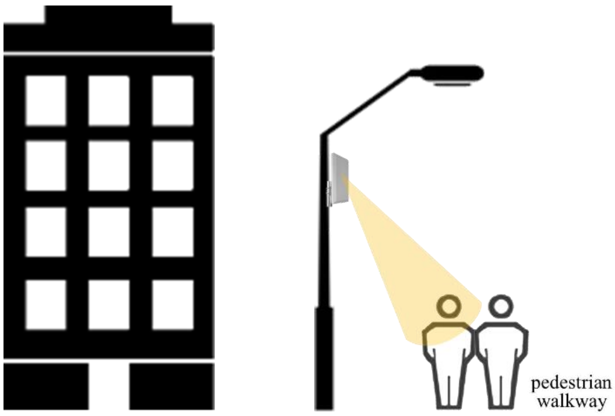

Figure 3-4: Illustration of RBSs installed on lamp posts.

<u>*Indoor RBSs*</u>

As illustrated in Figure 3-5, indoor RBSs are mounted on walls or on the ceiling in indoor environments. In general, for indoor environment with low ceiling height, RBS antennas could be in close proximity to public-accessible areas, and so there are more stringent considerations for the EMF emission levels of RBSs.

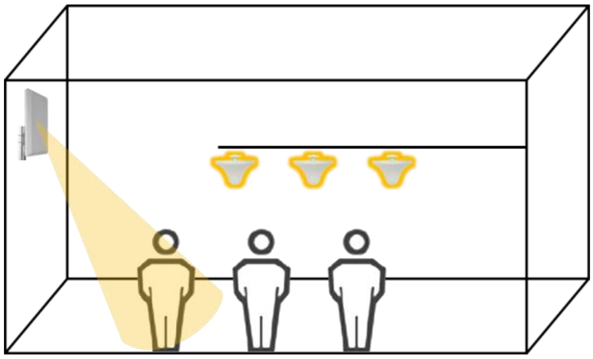

Figure 3-5: Illustration of indoor RBSs.

RBSs installed at external wall of buildings

As illustrated in Figure 3-6, RBSs installed at external wall of buildings could be at different heights above nearby pedestrian walkways and could be in close proximity to nearby buildings. EMF emission levels of the RBSs should be limited such that the NIR level at the nearest public-accessible areas – at nearby pedestrian walkways or buildings – are always compliant with the ICNIRP guidelines.

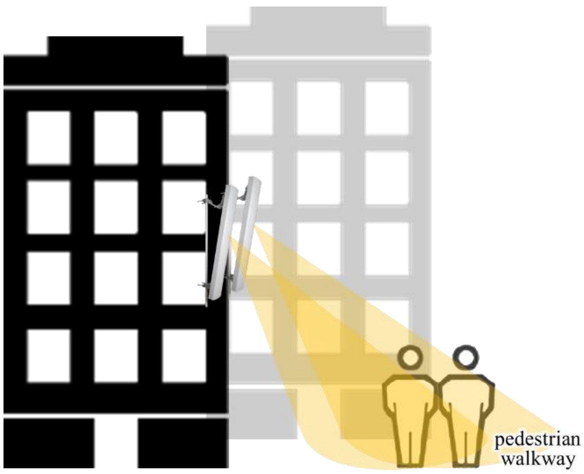

Figure 3-6: Illustration of RBSs installed at external wall of buildings.

3.2 Regulatory Measures on NIR Safety of RBSs Adopted by Hong Kong

In Hong Kong, the CA adopts the ICNIRP safety limits in formulating regulatory measures for ensuring radiation safety of RBSs **[Ref 10]**. Such NIR safety limits were based on the ICNIRP 1998 guidelines **[Ref 5]** and they are still applicable under the ICNIRP 2020 guidelines **[Ref 1]** (see Section 2.1.2.3).

3.2.1 Controlling the Maximum Allowable Transmitting Power of RBSs and Restrictions on RBS Installation Locations

MNOs are required to obtain approvals of OFCA acting for the CA before bringing their RBSs into operation. In vetting the applications, apart from examining the NIR level of individual RBSs, OFCA will consider the NIR level contributed by all RBSs installed at the same location to ensure that the aggregate NIR level complies with the ICNIRP guidelines before granting approval for the applications (see Section 2.1.1.2 and Section 5). The application procedures and constraints for installation of RBSs under different deployment scenarios are detailed in **[Ref 11] [Ref 12] [Ref 13]** and discussed in the following paragraphs[24].

Rooftop RBSs, RBSs installed on external wall of buildings, and indoor RBSs

As detailed in **[Ref 11]**, when an MNO applies for setting up an RBS at a particular location, it needs to provide OFCA with the technical particulars of the proposed RBS (including the exact location, size and dimensions of equipment and antenna, operating frequencies, emission power, etc.) and declare compliance with the requirements on radiation safety.

[24] Practical recommendations on whether there is any room to relax or tighten the existing regulatory controls on the emissions of RBSs taking into account the public concern on radiation safety are presented in Section 7.

RBSs installed on sheltered bus stops

As detailed in **[Ref 12]**, MNOs are required to follow the prevailing procedures and requirements to apply to OFCA for approval before bringing RBSs installed on sheltered bus stops into operation. The transmitting power per antenna of the RBSs should in general not exceed 2W effective radiated power[25] ("ERP"). For RBSs that operate at the 26 and 28 GHz bands and their antenna(s) are at least 3m above pedestrian walkway, a transmitting power of not exceeding 10W ERP might be approved subject to the demonstration of compliance with the requirements on radiation safety.

RBSs installed on payphone kiosks

As detailed in **[Ref 13]**, MNOs are required to follow the prevailing procedures and requirements to apply to OFCA for approval before bringing RBSs installed on payphone kiosks into operation. The aggregate transmitting power per antenna should not exceed 2W ERP.

Approval of low power indoor RBSs[26]

Since low power indoor RBS with an EIRP no more than 2W and installed indoors or within buildings cause low level of NIR, MNOs could perform self-service registration of such low power indoor RBSs via a web-based platform and instant approval will be given upon successful registration.

[25] By definition, the EMF emission level of an RBS antenna can be expressed in terms of the EIRP or the ERP, where the EIRP level is equivalent to the ERP level plus 2.15dB.

[26] See https://www.ofca.gov.hk/filemanager/ofca/en/content_757/traac6_2020.pdf.

3.2.2 NIR Monitoring Mechanisms

OFCA adopts a three-pronged approach for NIR monitoring:

1) Requiring MNOs to submit report of NIR measurements in the vicinity of the newly operating RBSs within four weeks from the commencement of operation (see Section 3.2.1);

2) Conduct annual exercises to perform sample-checks of approved RBS for on-site NIR measurements; and

3) Providing free service of on-site NIR measurements in response to requests of the general public.

The above approach allows OFCA to maintain updated NIR records as new RBSs are brought into operation and to assess their impacts to the public in a timely fashion. Since the environments in the vicinity of RBSs could change over time, sample-checks by on-site NIR measurements can further ensure that the requirements on radiation safety continue to be met. The free service for on-site NIR measurements in response to public requests can enable OFCA to detect and mitigate potential NIR risks as well as to address concerns of the general public. More specifically, for such request from the general public, OFCA will conduct on-site inspections, measure NIR levels inside their premises, and explain the measurement results to the concerned public.

3.2.3 NIR Measurement Methodologies and Presentation Approaches on the Result of NIR Compliance for Different Audiences

As discussed in Section 2.1.1.2, compliance with the ICNIRP guidelines could be demonstrated based on the broadband NIR level as well as frequency-specific NIR level, i.e. Broadband Measurements should be made for initial verification whether the NIR levels are sufficiently low, and Frequency-specific Measurements should be made if there is a need for determining the dominant source(s) of NIR. As of 2022, OFCA possesses equipment for conducting Broadband Measurements over all mobile service frequency bands (in the frequency range from 600 MHz to 43.5 GHz) as well as equipment for conducting Frequency-specific Measurements over sub-6 GHz frequency bands[27].

Different audiences may have different perspectives and concerns towards NIR safety, and different presentation approaches may be used for effective explanation on the findings. For the general public, the primary concern is whether their premises are safe. Therefore, the general public should be provided with the essential information that the broadband NIR level in their premises is below a threshold level equivalent to certain percentage of the most stringent ICNIRP safety limits (see equation (2-4)). If the broadband NIR level exceeds the threshold level, on a case-by-case basis, the general public should be provided with Frequency-specific Measurement results and the ICNRIP compliance level percentage (see equation (2-3)). For people who need to assess NIR safety as part of their professional duties (such as regulatory bodies and MNOs), it is most intuitive to express NIR levels in terms of incident power density S_{inc} in Wm^{-2} and it is straight forward to determine the ICNRIP compliance level percentage if the power density levels of all EMF sources are known (see equation (2-3)). It should be

[27] See Section 6.3.1 for a selection of equipment that could be used for conducting Broadband Measurements and Frequency-specific Measurements.

noted that NIR level can be *equivalently* presented in terms of incident power density S_{inc} in Wm^{-2}, incident electric field strength E_{inc} in Vm^{-1}, or incident magnetic field strength H_{inc} in Am^{-1} since these parameters are interconvertible as elaborated in Section 2.1.1.1 based on equation (2-1).

3.2.4 Public Education Campaigns

OFCA maintains a website[28] providing extensive information on radiation safety of RBSs and hand-held radiocommunications devices. For people who design or operate radio systems, or work at radio sites, OFCA published a code of practice to give guidance for the protection of workers and the general public from exposure to radio frequency EMFs **[Ref 10]**. For the general public, OFCA has produced various publicity materials on radiation safety of RBS including information leaflet, poster, as well as radio and television announcements to the public interests[29]. In summary, OFCA's public education campaign can reach out to audiences with different perspectives and concerns towards NIR safety. One area for improvement is to publish NIR measurement results of sampled public areas on OFCA's website similar to some regulatory bodies in overseas economies.

3.3 Notable Regulatory Measures on NIR Safety of RBSs Adopted by the United Kingdom, Australia, New Zealand, the United States, Germany, and Singapore

Similarly to Hong Kong, the United Kingdom, Australia, New Zealand, the United States, Germany, and Singapore also adopted the ICNIRP safety limits to establish their regulatory

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[28] See https://www.ofca.gov.hk/en/consumer_focus/guide/safety/rf_radiation_safety/index.html.

[29] See https://www.ofca.gov.hk/filemanager/ofca/Publicity/en/upload/10/2e.pdf, https://www.ofca.gov.hk/en/consumer_focus/galley/video/index_id_66.html, https://www.ofca.gov.hk/filemanager/ofca/Publicity/en/upload/46/Base_Station_Poster.pdf, and https://www.ofca.gov.hk/en/consumer_focus/galley/video/index_id_65.html.

measures on NIR safety of RBSs. Table 3-1 provides an overview of the technical references adopted by these jurisdictions.

Table 3-1: Overview of the technical references adopted by the United Kingdom, Australia, New Zealand, the United States, Germany, and Singapore for radiation safety of RBS.

Jurisdiction	Technical Reference	Further Information
United Kingdom	ICNIRP	N/A
Australia	ARPANSA (referenced to ICNIRP)	• The exposure limits for mobile service frequency bands are the same as the ICNIRP guidelines • Includes other requirements on verification of compliance
New Zealand	Standards New Zealand: NZS 2772.1 (based on ICNIRP)	• The exposure limits for mobile service frequency bands are the same as the ICNIRP guidelines • Variations on implementation and verification of compliance
United States	IEEE and NCRP (referenced to ICNIRP)	• The exposure limits for mobile service frequency bands are less restrictive than ICNIRP guidelines
Germany	ICNIRP	N/A
Singapore	ICNIRP	N/A

Some notable regulatory practices adopted by these economies are summarized in the following sections.

3.3.1 Controlling the Maximum Allowable Transmitting Power of RBSs and Restrictions on RBS Installation Locations

RBS deployment sites with low total radiated power in Germany[30]

In Germany, an RBS with transmitting power above 10W EIRP may only be operated if a valid location certificate is obtained for this location. The same applies to an RBS with transmitting power less than 10W EIRP, which is installed at a location with a *total* radiated power above 10W EIRP, or if the additional RBS results in the total radiated power exceeding the 10W EIRP.

[30] See http://www.gesetze-im-internet.de/bemfv/.

To obtain a location certificate, an MNO needs to submit an application to the regulatory body (i.e., the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railways) with technical particulars of the proposed RBS (including the exact location, size and dimensions of equipment and antenna, operating frequencies, emission power, etc.). For a location certificate to be issued, compliance with the relevant exposure limits need to be demonstrated mathematically or by measurement in public-accessible areas (see Section 3.1 for discussions on the different RBS deployment scenarios).

3.3.2 NIR Monitoring Mechanisms

NIR monitoring led by regulatory body in the United Kingdom

In the United Kingdom, Ofcom performs sample-checks to measure the NIR levels near RBS deployment sites and publish the measurement results on their website[31]. The public may also request for on-site NIR measurements as a chargeable service[32].

NIR monitoring commissioned by MNOs in New Zealand

In New Zealand, MNOs regularly commissions a competent body (e.g., a consulting firm specializing in specialist measurement and advisory services on EMFs, NIR and health) for independent monitoring of NIR levels near RBS deployment sites and the measurement results are published on the Ministry of Health's website[33].

[31] See https://www.ofcom.org.uk/spectrum/information/mobile-operational-enquiries/mobile-base-station-audits.

[32] See https://www.ofcom.org.uk/spectrum/information/mobile-operational-enquiries/audit-info.

[33] See https://www.health.govt.nz/our-work/environmental-health/non-ionising-radiation/independent-cellsite-monitoring.

3.3.3 NIR Measurement Methodologies and Presentation on the Result of NIR Compliance

Broadband and Frequency-specific Measurements in the United Kingdom and New Zealand

In the United Kingdom and New Zealand, NIR measurement results for both Broadband and Frequency-specific Measurements (see Section 2.1.1.2) are published. In general, Frequency-specific Measurement results are presented as a percentage of the compliance level.

3.3.4 Public Education Campaigns

In each economy, the regulator publishes extensive online materials to educate the public about radiation safety and to refute misinformation[34].

3.4 Summary of Recommendations for Enhancing the Regulatory Measures on NIR Safety of RBSs Adopted by Hong Kong

In summary, as of 2022, the regulatory measures adopted by Hong Kong are on par with internationally accepted guidelines on radiation safety, and OFCA employs similar mechanisms for NIR measurements and monitoring as other international counterparts. However, the regulatory measures on NIR safety of RBSs adopted by Hong Kong can be enhanced in the following aspects:

- The United Kingdom, New Zealand, and Germany published RBS NIR measurement results in the websites of the regulatory bodies, whereas RBS NIR measurement results in Hong Kong are not available for public access. To enhance

[34] See https://www.acma.gov.au/eme-5g-and-you, https://www.health.govt.nz/our-work/environmental-health/non-ionising-radiation, and https://www.ofcom.org.uk/manage-your-licence/emf/policy.

Hong Kong public's awareness and confidence in NIR safety of RBSs, OFCA can publish with discretion the NIR measurement results of public areas.

- OFCA has a simplified and efficient procedure for processing low power indoor RBSs that cause low level of NIR. OFCA can consider extending this procedure for approval of low power RBSs in other deployment scenarios (e.g., similar to the practice adopted by Germany).

4 Interviews and Technical Exchange With Hong Kong MNOs and RBS Vendors Addressing RBS Deployment Strategies and RBS Technical Specifications

Interviews and technical exchange meetings were held with representatives of Hong Kong MNOs (i.e., Hong Kong Telecommunications (HKT) Ltd., Hutchison Telephone Company Ltd., SmarTone Mobile Communications Ltd., and China Mobile Hong Kong Company Limited) to inquire about their RBS deployment strategies in the 5G era and beyond and with RBS equipment vendors (i.e., Huawei International Co., Ltd. and Ericsson (HK) Ltd.) to inquire about their RBS technical specifications.

Deploying RBSs installed on street furniture

Hong Kong MNOs anticipated that they would need to deploy more RBSs installed on street furniture for enhancing service coverage. Due to physical limitations on installing RBSs (or RBS antennas) on street furniture, only few RBSs (or RBS antennas) could be deployed on the same site. Conventionally, RBSs installed on street furniture have low EMF emission levels and small coverage areas. Hong Kong MNOs are exploring the feasibility of using RBS installed on street furniture for providing mobile services over larger coverage areas.

Deploying RBSs that make use of mMIMO antennas

Hong Kong MNOs anticipated that more RBSs would be deployed making use of mMIMO antennas for enhancing service capacity (i.e., beamforming can concentrate signals in the directions towards targeted receivers thus improving signal quality and avoiding interference). In terms of NIR safety, Hong Kong MNOs and RBS equipment vendors indicated that their RBSs that made use of mMIMO antennas deployed in Hong Kong could be configured in such a way that the average EMF emission level of signal beams pointing towards a given direction would be limited to a certain fraction of the maximum transmitting power level (see Section 2.2). Under such configuration, the NIR level within the RBS coverage area can be substantially lowered[35] and would not be affected irrespective of how user terminals would be distributed in the RBS coverage area (see Figure 2-4).

Deploying mmWave RBSs

Hong Kong MNOs would expect to gradually deploy RBSs that operate at mmWave frequency range. At the time of this study, mmWave RBSs available in the market always use mMIMO antennas with relatively large physical dimensions not favorable for indoor deployment. Moreover, there were also small number of compatible hand-held mobile communications devices supporting mmWave band meanwhile. Hong Kong MNOs and RBS equipment vendors indicated that new mmWave RBS products would be introduced in 2022 and they would anticipate an increase in mmWave RBS deployment in the future.

[35] This behavior is verified in field measurements and the measurement results are presented in Section 6.3.2.

5 Assessment Models for Evaluating NIR Levels From RBSs for Exercising Regulatory Controls

In practice, a given location may have one or more RBSs operating in one or more frequency bands as illustrated in Figure 5-1. Such deployment scenarios include i) a single RBS operating in one particular frequency band, ii) a single RBS operating in multiple frequency bands, and iii) multiple RBSs in the vicinity operating in multiple frequency bands.

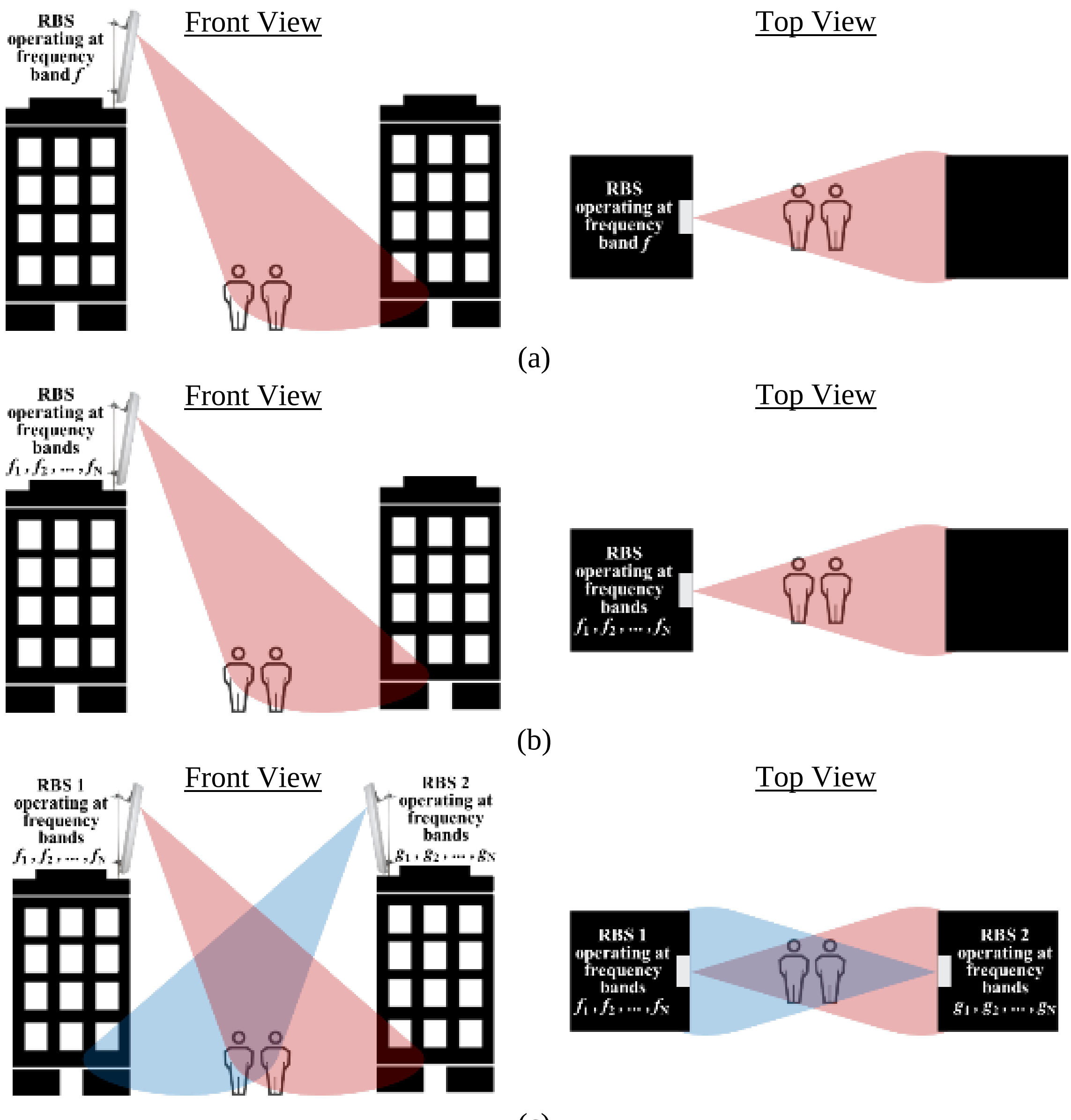


Figure 5-1: Illustration of multiple RBSs in the vicinity operating in different frequency bands at a given location: (a) A single RBS operating in one particular frequency band, (b) A single RBS operating in multiple frequency bands, (c) Multiple RBSs in the vicinity operating in a number of frequency bands

In this section, assessment models are presented for evaluating NIR levels from RBSs for exercising regulatory controls. Firstly, analytical models are introduced for predicting the aggregate NIR level of all RBSs installed at the same location, where these models could facilitate consideration of cases such as assessing the feasibility of bringing new RBSs into operation, or adjusting the transmitting power levels of existing RBSs in the vicinity to ensure that the aggregate NIR level continue to be compliant with the ICNIRP safety limits. After that, considerations for measurements of the aggregate NIR level at locations with multiple RBSs operating in multiple frequency bands are discussed.

5.1 Analytical Models For Predicting NIR Levels From a Single or Multiple RBSs Operating in One or More Frequency Bands

With reference to Section 2.1.1.2, at a given location the NIR levels from a single or multiple RBSs operating in one or more frequency bands can be expressed in terms of broadband incident power density $\sum_{\substack{y \in \text{EMFs in mobile} \\ \text{services freq. bands}}} S_{\text{inc},y}$ or frequency-specific incident power density $\{S_{\text{inc},y}\}_{\substack{y \in \text{EMFs in mobile} \\ \text{services freq. bands}}}$, where $S_{\text{inc},y}$ is the incident power density at a particular frequency band. Based on the broadband incident power density or the frequency-specific incident power density, the ICNIRP compliance level can be determined using equation (2-4).

Theoretical Model

In Section 2.2, a theoretical model is presented for evaluating incident power density from a single RBS operating in one particular frequency band. As shown in equations (2-5) and (2-6), the theoretical model takes into account the technical particulars of the RBS (including the radiation pattern of the antenna, the distance and orientation between the RBS antenna and the observation point, etc.). The theoretical model could evaluate NIR level in three-dimensional space, where the NIR level is higher in the direction of the main lobe of the antenna radiation pattern and is lower in directions outside of the main lobe. When there is a single RBS operating in multiple frequency bands, the theoretical model can be similarly applied for evaluating incident power density generated by the RBS operating in *each* frequency band. By the same analogy, when there are multiple RBSs in the vicinity operating in a number of frequency bands, the analytical model can be similarly applied for evaluating incident power density generated from *each* RBS operating in *each* frequency band. Leveraging the theoretical model, it is feasible to predict the broadband and frequency-specific NIR levels and determine the ICNIRP compliance level for locations with a single or multiple RBSs operating in one or more frequency bands. In general, the theoretical model could be applied to quantitatively analyze NIR levels from RBSs for the specific use cases (see Annex G and Section 6.2).

Simplified Model

For typical use cases, the primary objective of regulatory control is to ensure that the aggregate NIR level of all RBSs installed at the same location are sufficiently low in public-accessible areas so that NIR safety can be guaranteed. To fulfill this objective, preliminary analysis of the NIR level at a location under consideration could be *extrapolated* from typical bounds obtained through approximations or field measurements. Specifically, for a given RBS deployment scenario (e.g., rooftop RBS), based on a bound on the NIR level for a single RBS operating in one particular frequency band, assessment of the aggregate NIR level could be made by proportionally upscaling the bound on the NIR level taking into account the total number of RBSs and the frequency bands that they operate on (see Annex G).

5.2 Considerations for Measurements of the Aggregate NIR Level at Locations With Multiple RBSs Operating in Multiple Frequency Bands

As discussed in Section 2.1.1.2, Broadband Measurements and Frequency-specific Measurements could both be used for assessing NIR levels from multiple RBSs in the vicinity operating in a number of frequency bands. When measuring the aggregate NIR level at locations with multiple RBSs operating in multiple frequency bands, Broadband Measurements can be made for initial verification whether the NIR levels are sufficiently low, and Frequency-specific Measurements can be made if there is a need for determining the dominant source(s) of NIR.

6 Investigation on NIR Levels From RBSs in Representative Locations of Hong Kong via Computer Simulations and Field Measurements

According to the past measurements by OFCA, the NIR levels in public-accessible areas in Hong Kong are historically well below the ICNIRP safety limits (see Section 7.1). To facilitate the provision of mobile services in Hong Kong in the 5G era and beyond while safeguarding NIR safety, a thorough investigation has been carried out to evaluate NIR levels generated from RBSs in representative locations of Hong Kong with the objectives of exploring whether and how the regulatory controls on EMF emission levels of RBSs can be enhanced. This investigation included computer simulations as well as field measurements for characterizing NIR levels due to 1) different RBS deployments scenarios, 2) different combination of RBS technologies, 3) different combinations of the use of mobile service frequency bands, 4) the use of mMIMO antennas as well as the use of conventional non-mMIMO antennas, and 5) different distances and orientations between RBS antennas and public-accessible areas.

6.1 Overview of Test Cases and Observations to Be Drawn

A collection of test cases is designed to cover all the technical and physical specifications of RBS deployment scenarios as of 2022 and it is summarized in Table 6-1. It should be noted that the aggregate NIR level from 2G to 5G RBSs depends on the emission levels of each RBS on each frequency band and the total number of frequency bands being deployed (see Section 5).

Table 6-1: Summary of technical and physical specifications of RBS deployment scenarios as of 2022.

RBS Deployment Scenarios	RBS Technologies	Mobile Services Frequency Bands[36]	RBS Antenna Technologies	Environment
• Rooftop RBSs • RBS installed at external wall of a building • RBSs installed on street furniture (such as payphone kiosks, sheltered bus stops and lamp posts) • Indoor RBSs	• 2G • 3G • 4G • 5G	• 850 MHz • 900 MHz • 1800 MHz • 2100 MHz • 2300 MHz • 2600 MHz • 3300 MHz • 3500 MHz • 4900 MHz • 26/28 GHz	• Conventional non-MIMO antenna • mMIMO antenna	• RBS antenna faces public-accessible areas • RBS antenna at high height and there is a longer distance separation between the antenna and public-accessible areas • RBS antenna at low height and there is a relatively shorter distance separation between the antenna and public-accessible areas

Based on the researches, site surveys, and recommendations from Hong Kong MNOs, ten RBS deployment sites have been selected for this study as summarized in Table 6-2. The selected test sites are categorized as *Group A*, *Group B*, *Group C*, and *Group D* for drawing different observations. For *Group A* to *Group C* sites, it is necessary to trigger RBS transmission (i.e., by performing data downloading with one or more user terminals) to facilitate the verification of mMIMO beamforming operations and characterizing the *worst case* NIR levels. For *Group D* sites, it is not necessary to trigger RBS transmission to facilitate the characterizing of the *typical* NIR levels however.

1) *Group A* sites: To investigate the technical behaviors of RBSs that make use of mMIMO antennas
2) *Group B* sites: To verify that the ICNIRP safety limits can still be met even though the transmitting power of the RBSs are increased
3) *Group C* sites: To investigate the NIR level for RBS antennas placed at different height and distances separation from public-accessible areas
4) *Group D* sites: To investigate the NIR level with multiple RBSs in the vicinity

[36] At the time of this study, the 700 MHz band is recently assigned for provision of public mobile services but RBSs operating in this frequency band have not been deployed.

Table 6-2: Summary of RBS deployment sites selected for investigating NIR levels in representative locations of Hong Kong and observations to be drawn.

<table>
<tr><th>Group</th><th>Test Site</th><th>Descriptions of Targeted RBSs</th><th>Observations to Be Drawn</th><th>Trigger RBS Trans-mission</th><th>Computer Simulations</th></tr>
<tr><td rowspan="2">A</td><td>1</td><td>RBSs at a rooftop at low height including one sub-6 GHz RBS that makes use of mMIMO antenna
• RBS technologies: 4G, 5G
• RBS frequency bands: 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz, 2600 MHz, 3500 MHz, 4900 MHz</td><td rowspan="2">• To demonstrate mMIMO beamforming operations and to characterize the EMF emission level of signal beams pointing towards a given direction</td><td rowspan="8">Yes</td><td rowspan="2">No</td></tr>
<tr><td>2</td><td>Indoor mmWave RBS that makes use of mMIMO antenna
• RBS technologies: 5G
• RBS frequency bands: 28 GHz</td></tr>
<tr><td rowspan="2">B</td><td>3</td><td>RBSs at a rooftop at low height
• RBS technologies: 4G, 5G
• RBS frequency bands: 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz, 2600 MHz, 3500 MHz</td><td rowspan="2">• To investigate the NIR level when RBS antennas have relatively shorter distance to public-accessible areas
• To verify that the ICNIRP safety limits can still be met when the transmitting power levels of the RBSs are increased</td><td rowspan="2">Yes</td></tr>
<tr><td>4</td><td>RBSs installed on bus shelter (street furniture)
• RBS technologies: 3G, 4G, 5G
• RBS frequency bands: 1800 MHz, 2100 MHz, 3500 MHz, 28 GHz</td></tr>
<tr><td rowspan="4">C</td><td>5</td><td>RBSs at a podium facing a footbridge
• RBS technologies: 3G, 4G, 5G
• RBS frequency bands: 850 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz, 3500 MHz</td><td>• To investigate the NIR level for RBS antennas with different heights and distances from public-accessible areas
○ Smaller height difference and distance separation between antenna and pedestrians on footbridge
○ Larger height difference and distance separation between antenna and pedestrians on streets</td><td rowspan="4">Yes</td></tr>
<tr><td>6</td><td>RBSs installed on lamp pole (street furniture)
• RBS technologies: 4G, 5G
• RBS frequency bands: 1800 MHz, 2100 MHz</td><td>• To investigate the NIR level when RBS antenna has relatively shorter height difference and distance separation from public-accessible areas including under the lamp pole, along the sidewalk, etc.</td></tr>
<tr><td>7</td><td>RBSs installed at external wall of a building
• RBS technologies: 2G, 3G, 4G, 5G
• RBS frequency bands: 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz, 26 GHz</td><td>• To investigate the NIR level with multiple RBSs in the vicinity</td></tr>
<tr><td>8</td><td>RBSs at a rooftop at low height in rural area
• RBS technologies: 3G, 4G, 5G
• RBS frequency bands: 850 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz, 3500 MHz</td><td>• To investigate the NIR level when RBS antennas have relatively shorter distance separation to public-accessible areas</td></tr>
<tr><td rowspan="2">D</td><td>9</td><td>Indoor RBSs in shopping center</td><td rowspan="2">• To investigate the NIR level when RBS antennas have relatively shorter distance separation to public-accessible areas
• To investigate the NIR level with multiple RBSs in the vicinity</td><td rowspan="2">No</td><td rowspan="2">No</td></tr>
<tr><td>10</td><td>Black spot with multiple RBS sites in the vicinity</td></tr>
</table>

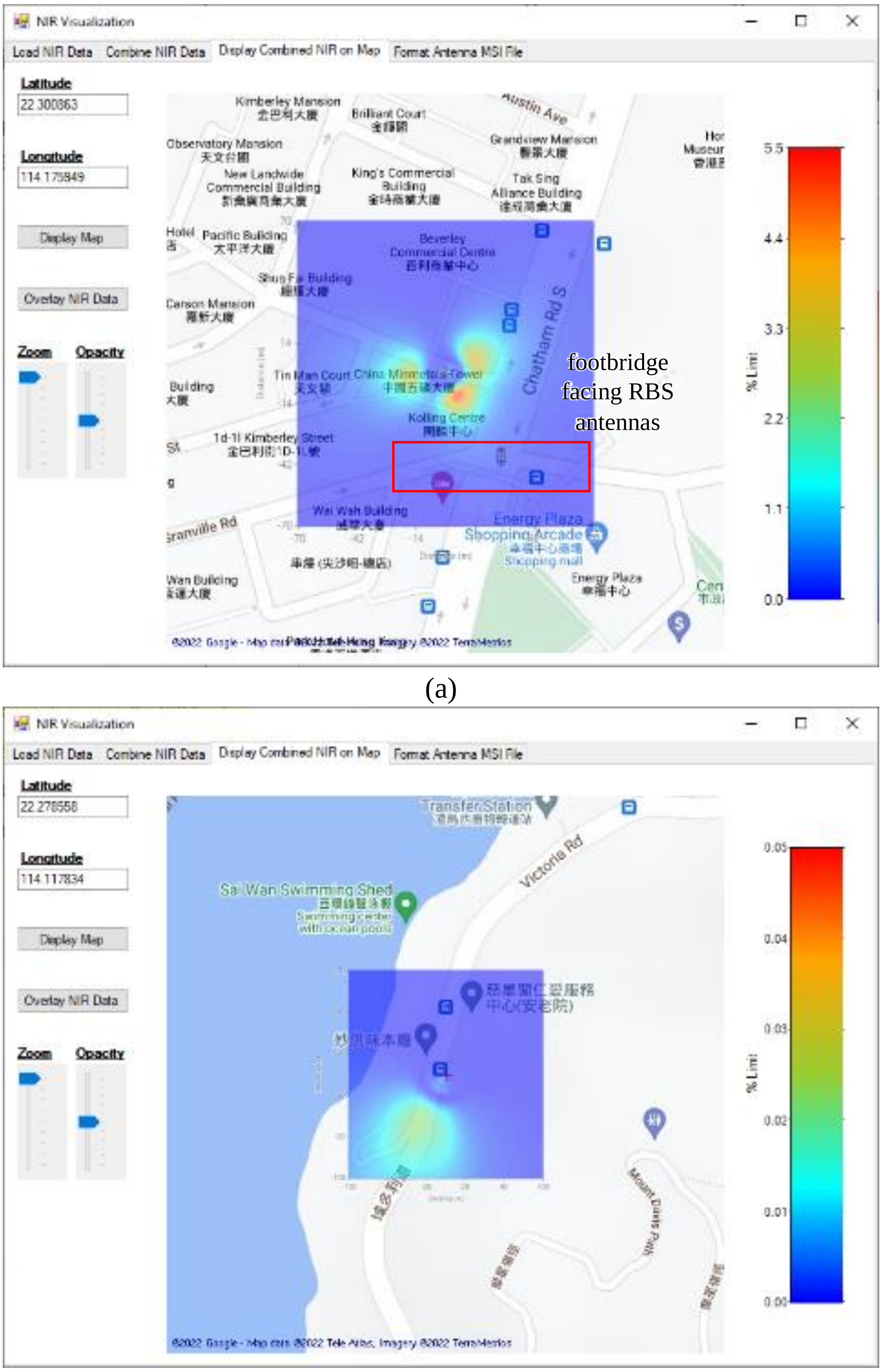
As summarized in Table 6-2, computer simulations are conducted to model NIR levels of *Group B* and *Group C* sites, and they are not conducted for *Group A* and *Group D* sites due to the following reasons:

- For *Groups A* sites, the technical behaviors of RBSs that make use of mMIMO antennas are subject to vendor specific design and are not available, and thus could not be modeled in computer simulations; and
- For *Group D* sites, the environments are too complex for accurate modeling in computer simulations that is beyond the scope of this study. On one hand, indoor RBSs in shopping center often make use of distributed antenna system and each antenna could be shared by different combinations of low power RBSs operating in one or more frequency bands. On the other hand, detailed simulations of black spots with multiple RBS sites in the vicinity would require modeling the blockage effects of nearby building structures which are not readily available.

6.2 Computer Simulations for Predicting NIR Levels From RBSs

Computer simulations[37] are conducted for predicting NIR levels in the vicinity of RBS deployment sites. The computer simulations apply the theoretical model introduced in Section 5.1 for predicting the NIR level from each RBS under consideration and determining the ICNIRP compliance level of the aggregated NIR level from all RBSs as shown in equation (2-4). Simulation results on Test Sites 3 to 8 (see Table 6-2) show that the NIR levels from these RBSs at public-accessible areas are below 5% of the ICNIRP safety limits. For illustration, Figure 6-1 shows the simulated NIR levels from RBSs for Test Site 5 and 6.

[37] See Annex G for an overview of the computer simulation methodology.



(a)

(b)

Figure 6-1: Computer simulation results on NIR levels from RBSs for
(a) Test Site 5 at the height of a nearby footbridge, and (b) Test Site 6 at street level.

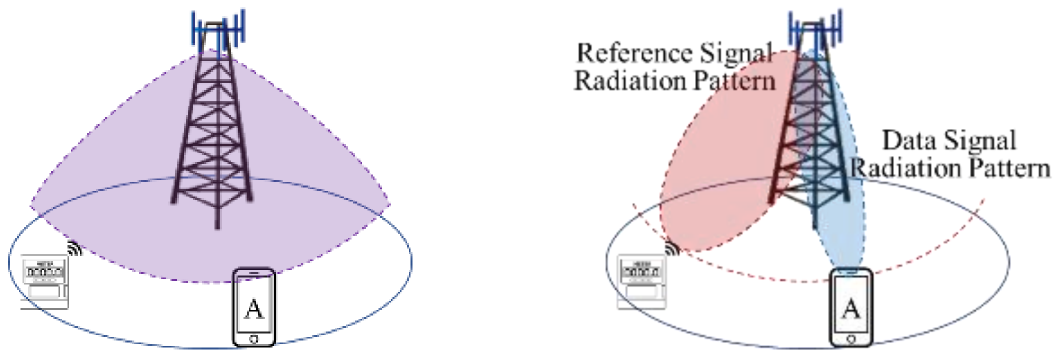
6.3 Field Measurements for Assessing NIR Levels From RBSs

General considerations for making NIR measurements

Figure 6-2 compares signal transmission of an RBS that makes use of a conventional non-mMIMO antenna with an RBS that makes use of a mMIMO antenna.

- As shown in Figure 6-2a, the RBS that makes use of conventional non-mMIMO antenna transmits signals uniformly within the entire service coverage area. As a result, the NIR level throughout the entire service coverage area changes with RBS traffic load regardless of where the users are situated.
- As shown in Figure 6-2b, an RBS that makes use of mMIMO antenna transmits signals using directional beams towards the target users. As a result, the NIR level in areas near the users would increase with increasing traffic load, whereas NIR level in areas without users would be much lower as compared with the case of using conventional antenna.

Based on the preceding discussions, NIR measurements should be made during day time reflecting normal traffic conditions, or in association with data downloading using one or more terminals to simulate the traffic conditions.



(a) (b)

Figure 6-2: Illustration of signal transmission by an RBS (a) that makes use of conventional non-mMIMO antenna and (b) that makes use of mMIMO antenna.

Broadband Measurements and Frequency-specific Measurements

Broadband Measurements and Frequency-specific Measurements could be used for assessing NIR levels from RBSs (see Section 2.1.1.2), i.e., Broadband Measurements are effective for initial verification whether NIR levels are sufficiently low, and Frequency-specific Measurements are required for determining the NIR level of specific frequency bands and from specific RBSs.

6.3.1 Field Measurement Equipment

Table 6-3 summarizes the equipment used in field measurements with details on 1) the type of NIR measurement that each equipment is used for, as well as 2) the technical specifications of each equipment. It should be noted that Frequency-specific Measurements are made at all test sites using a network scanner to measure the RBS reference signal level and then estimating the total NIR level using the methodologies discussed in Section 2.1.2.2 and Annex E. A portable spectrum analyzer is used for Frequency-specific Measurements at *Group A* sites only to facilitate characterizing the NIR level from mMIMO signal beams pointing towards a given direction. The network scanner and the portable spectrum analyzer need to be operated with the suitable antenna (i.e., supporting sub-6 GHz frequency range or mmWave frequency range) depending on the RBS frequency bands used at each test site.

Table 6-3: Summary of equipment used in field measurements.

Equipment Descriptions	Measurement Type	Technical Specifications	Test Sites Used
Broadband power meter and probe	Broadband Measurements	• Support EMF measurements in the frequency range from 100 MHz to 60 GHz • Support incident power density (S_{inc}) measurements in the range from 0.0013 to 424.40 Wm^{-2} 	*Group B* to *Group D* sites
Network scanner	Frequency-specific Measurements	• Support 2G, 3G, 4G, and 5G RBS reference signal measurements 	*Group A* to *Group D* sites
Portable spectrum analyzer		• Support EMF measurements in the frequency range from 5 kHz to 31 GHz • Noise level as low as -163 dBm 	*Group A*
Antenna for measuring signals in mmWave frequency ranges		• Support EMF measurements in the frequency range from 18 GHz to 44 GHz 	*Group A* to *Group C* sites
Antenna for measuring signals in sub-6 GHz frequency ranges		• Support EMF measurements in the frequency range from 698 MHz to 6 GHz 	*Group A* to *Group D* sites
Terminal for performing data download to trigger RBS transmission	Broadband Measurements and Frequency-specific Measurements	• Support 5G and 4G • Support frequency bands 850 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz, 2600 MHz, 3300 MHz, 3500 MHz, 4900 MHz, 26/28 GHz • Support restricting connection to RBSs operating at specific frequency bands 	*Group A* to *Group C* sites

6.3.2 Field Measurement Procedures and Key Findings for *Group A* Sites

Test Site 1 and 2 (see Table 6-2) were selected for investigating the technical behaviors of RBSs that make use of mMIMO antennas[38].

Measurement procedures

1) Based on the RBS' technical specifications, the coverage areas are divided into a few non-overlapping regions A, B, and C as illustrated in Figure 6-4.

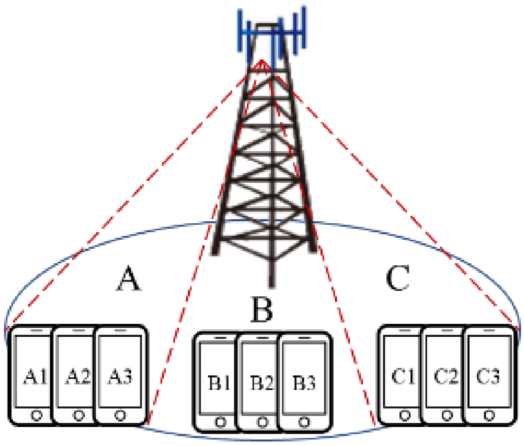


Figure 6-3: Illustration of dividing the RBS coverage area into non-overlapping regions for investigating the technical behaviors of RBSs that make use of mMIMO antennas.

2) For each non-overlapping region, the following measurements are performed:

Measurement	Measurements to Collect
1	• Use the network scanner to estimate the worst case NIR level from the RBS in this region (see Annex E)
2	• Use one terminal to perform data download and use the portable spectrum analyzer to measure the NIR level from the RBS in this region
3	• Use one additional terminal to perform data download and use the portable spectrum analyzer to measure the NIR level from the RBS in this region; repeat until the NIR level does not increase further. Monitor the NIR levels in all other regions.

3) Use multiple terminals to perform data download in every region and use the portable spectrum analyzer to measure the NIR level from the RBS in each region

[38] The detailed field measurement methods and results for Test Site 1 and 2 are presented in Annex H.

Key findings

1) The NIR level due to RBS emissions in each region is low when there is low data traffic load (e.g., no terminal is used to perform data download).

2) The NIR level in each region is not affected by data traffic load in other regions.

3) The NIR level in each region (in Wm^{-2}) is only 1/8 to 1/5 of the worst case NIR level from the RBS (estimated from measured reference signal)[39]. It should be noted that such results are specific to the technical specifications and configurations of the RBSs under study and reflect the situation for typical RBSs that make use of mMIMO antennas in Hong Kong (see Section 4).

6.3.3 Field Measurement Procedures and Key Findings for *Group B and Group C* Sites

Test Site 3 to 8 (see Table 6-2) were selected for investigating the NIR level for RBS antennas with different height and distances from public-accessible areas. Moreover, Test Site 3 and 4 were selected for verifying that the ICNIRP safety limits can still be met even though the transmitting power of the RBSs are increased[40].

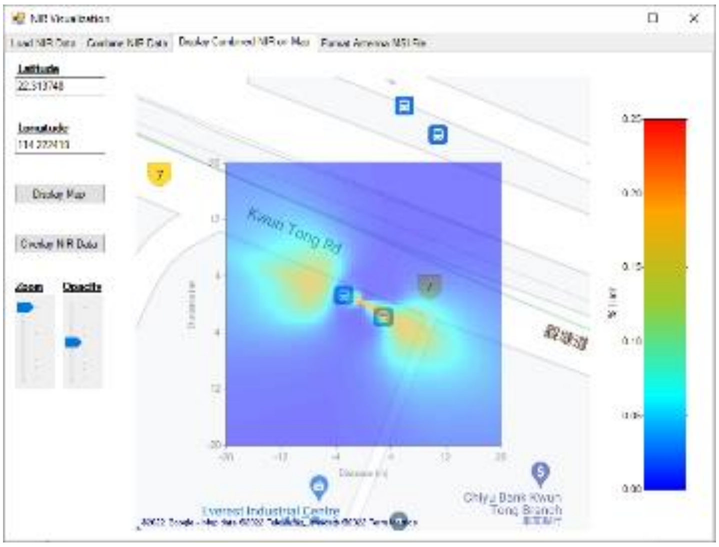
Measurement procedures

1) Based on the RBSs' deployment configurations and technical specifications, computer simulations are conducted to evaluate NIR levels generated from the RBSs. Measurement points can be selected from computer simulation results (e.g., positions expected to have relatively higher NIR levels) or along the directions of

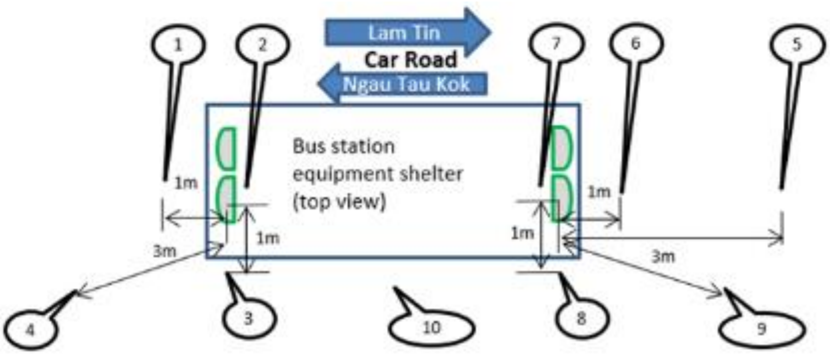
[39] See Section 2.2 for discussion on the time-averaged characteristics of mMIMO beamforming.

[40] The detailed field measurement methods and results for Test Site 3 to 8 are presented in Annex I.

the main lobe or side lobes of the radiation patterns of the RBS antennas. For illustration, Figure 6-4 shows the computer simulation results on NIR levels from RBSs and NIR measurement points for Test Site 4.



(a)



(b)

Figure 6-4: Test Site 4 (a) computer simulation results on NIR levels from RBSs, and (b) NIR measurement points.

2) Use terminals to perform data download from the target RBSs. At each measurement point, use the broadband power meter to make Broadband Measurements, and use the network scanner to make Frequency-specific Measurements. Based on the NIR measurements, assess the ICNIRP compliance level (see equation (2-4)). For illustration, Figure 6-5 shows the process of making NIR measurements at Test Site 3 and 4.

(a)

(b)

Figure 6-5: Illustration of making NIR measurements at Test Site 3 and 4.

Key findings

1) Field measurement results show that the NIR levels at public-accessible areas are below 5% of the ICNIRP safety limits.

2) Field measurement results at Test Site 3 and 4 show that the ICNIRP safety limits can still be met when the transmitting power of the RBSs are increased. These results suggest that the regulatory controls on the EMF emission levels of RBSs could possibly be relaxed.

3) Field measurement results at Test Site 5 suggest that even though a test location may see the RBS antennas with clear line of sight, the NIR level is actually very low because the RBS antennas are tilted or rotated pointing to other directions.

4) Field measurement results at Test Site 6 to 8 show that the NIR levels are well below the ICNIRP safety limits at locations near RBSs as installed on a lamp pole, near rooftop level RBSs installed at external wall of a building, and near RBSs at a rooftop at low height in rural area.

6.3.4 Field Measurement Procedures and Key Findings for *Group D* Sites

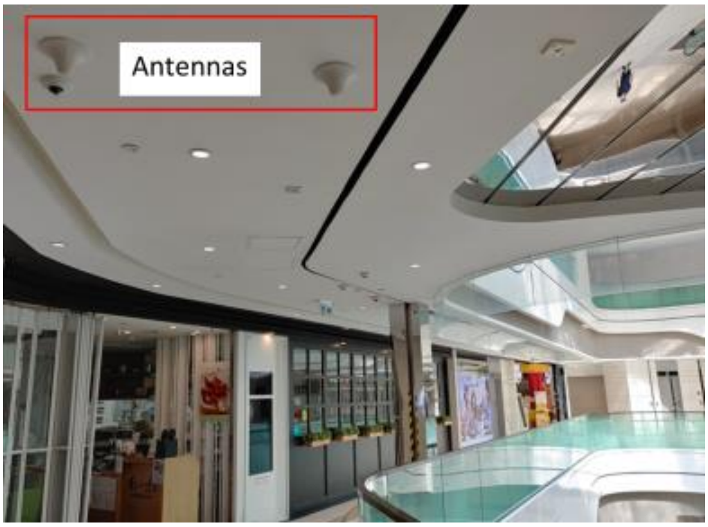
Test Site 9 and 10 (see Table 6-2) were selected for investigating the NIR level with multiple RBSs in the vicinity[41].

Measurement procedures

1) Based on the RBSs' deployment configurations, determine suitable measurement points (e.g., positions directly underneath or facing RBS antennas that are expected to have relatively higher NIR levels). Figure 6-6 shows the NIR measurement points for Test Site 9 and 10.

2) At each measurement point, use the broadband power meter to make Broadband Measurements and assess the ICNIRP compliance level (see equation (2-4)).

[41] The detailed field measurement methods and results for Test Site 9 to 10 are presented in Annex I.



(a)

(b)

Figure 6-6: Measurement points for Test Site 9 and 10. (a) NIR is measured near indoor RBS antennas at Test Site 9. (b) NIR is measured at street level facing RBS antennas (shown in green) at Test Site 10.

Key findings

1) Field measurement results at Test Site 9 and 10 show that the NIR levels are well below the ICNIRP safety limits even with multiple RBSs in the vicinity.

6.4 Summary

Based on computer simulations and field measurements of the NIR levels from RBSs in ten representative locations in Hong Kong, it was observed that in general the NIR levels at public-accessible areas are below 5% of the ICNIRP safety limits and the regulatory controls on the EMF emission levels of RBSs could possibly be relaxed for some RBS deployment scenarios. Moreover, field measurement results showed that the time-averaged NIR level from RBSs that make use of mMIMO antennas in Hong Kong is typically 1/8 to 1/5 of the worst case NIR level from the RBS (estimated from measured reference signal) due to the technical behaviors of mMIMO beamforming.

7 Historical NIR Levels From RBSs in Hong Kong and Recommendations for Enhancing the Control of Emissions of RBSs Under Different Deployment Scenarios in the 5G Era and Beyond

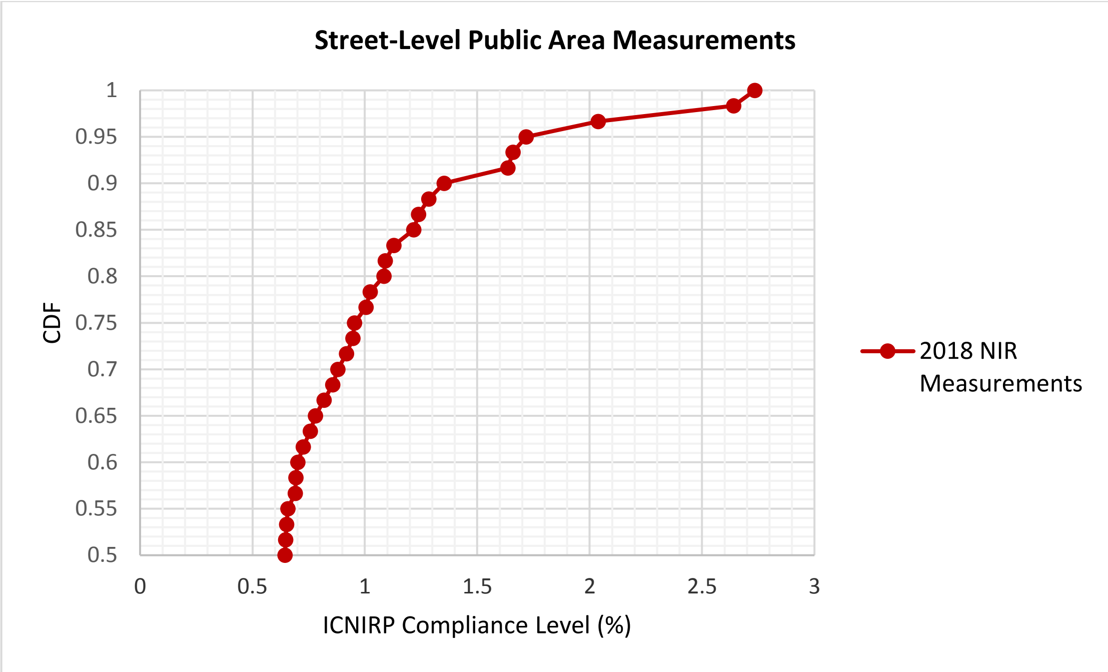
In this section, the NIR measurement statistics of Hong Kong are first presented for illustrating the historical NIR levels in public-accessible areas. To facilitate the continued development of mobile services, some recommendations are proposed for enhancing the control of emissions of RBSs under different deployment scenarios based on the NIR measurement statistics as well as various findings of this study (such as RBS technical specifications and Hong Kong's spectrum release plan). The emission levels of RBSs could be relaxed to satisfy the needs of various mobile services (i.e., in terms of speed, capacity, and coverage) while ensuring that NIR levels can continue to be maintained at low levels.

7.1 Historical NIR Levels From RBSs in Hong Kong

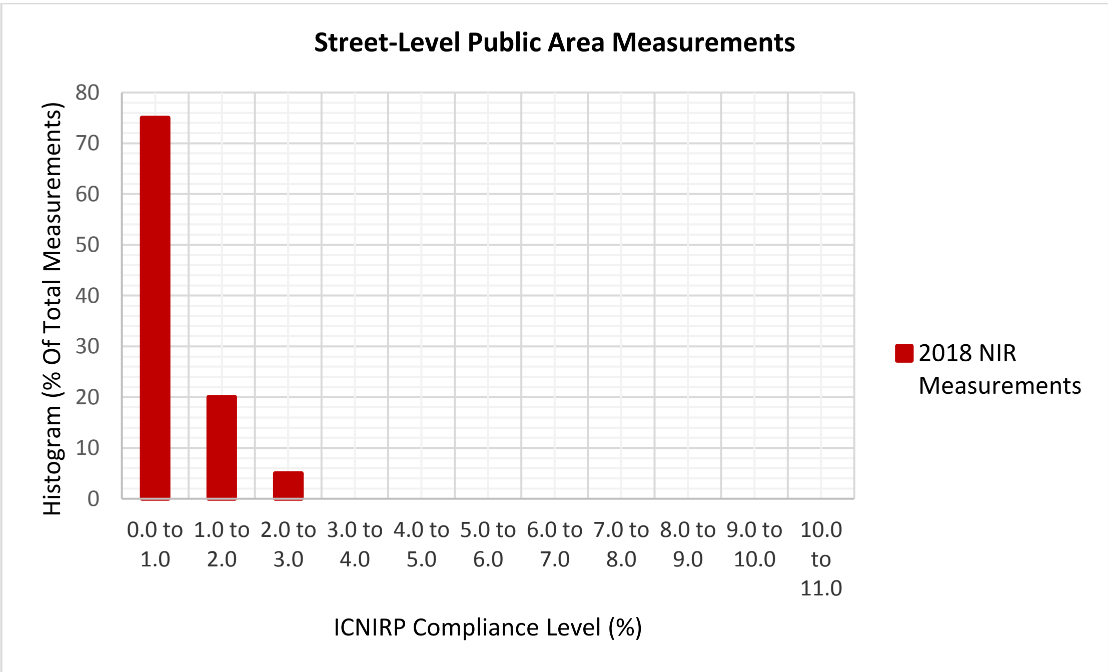
Figure 7-1 and Figure 7-2 show the statistics of NIR levels in public-accessible areas in Hong Kong including the cumulative distribution function ("CDF") and histogram of the ICNIRP compliance levels mainly attributed by outdoor RBS emissions at 850 MHz or above obtained through street-level measurements at sampled public areas and measurements at sampled households in the vicinity of RBSs as per request of the general public conducted by OFCA in[42,43] 2018.

[42] In 2018, the 850 MHz band was the lowest frequency band assigned for the provision of public mobile services. According to equation (2-4), the incident power density level corresponding to 850 MHz (see Table 2-3) is adopted for the calculation of the ICNIRP compliance level.

[43] Street-level measurements of NIR levels at sampled public areas in Hong Kong has been suspended in 2019-2021 due to social unrest and the outbreak of COVID-19.

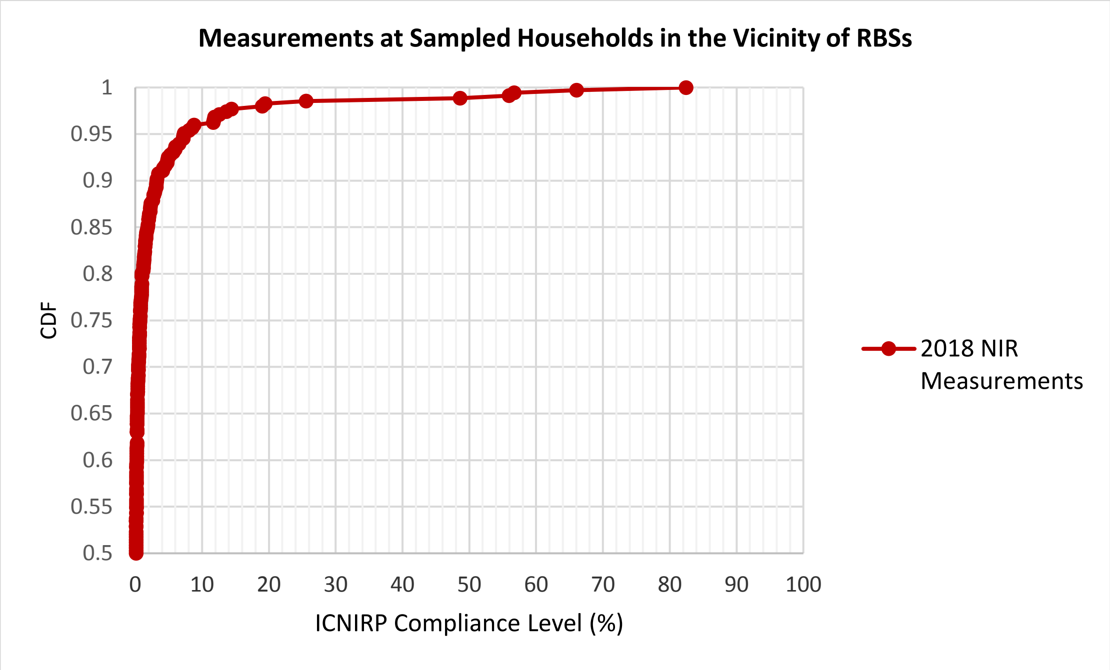


(a)

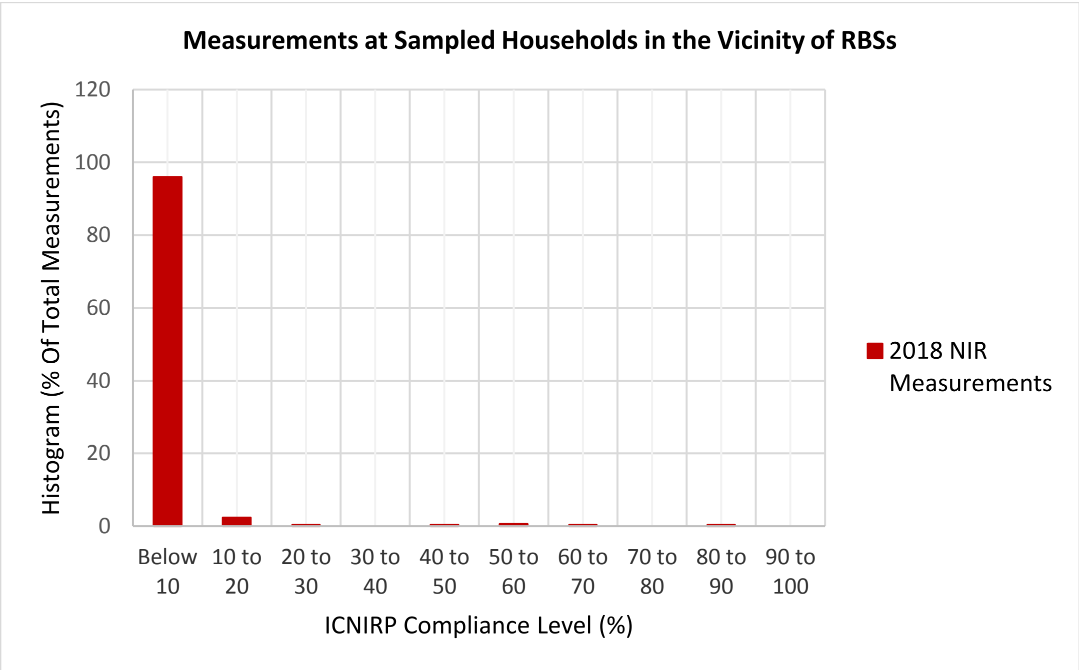


(b)

Figure 7-1: Statistics of NIR levels at street-level public-accessible areas in Hong Kong. (a) CDF and (b) histogram of ICNIRP compliance level of NIR measurements.



(a)



(b)

Figure 7-2: Statistics of NIR levels at sampled households in the vicinity of RBSs in Hong Kong. (a) CDF and (b) histogram of ICNIRP compliance level of NIR measurements.

It can be observed that at least 95% of the street-level public area measurements were below 5% of the ICNIRP compliance level, and 95% of the measurements at sampled households in the vicinity of RBSs were below 10% of the ICNIRP compliance level. These results show that the NIR levels in public-accessible areas in Hong Kong are well below the ICNIRP safety limits. However, the NIR levels from RBSs will evolve over time due to new RBS deployment scenarios, operation of RBSs on new frequency bands, etc. For example, since new frequency bands have been allocated for the provision of mobile services between 2018 and 2022, the NIR exposure levels for 2022 are expected to be higher than that of 2018.

7.2 Recommendations for Enhancing the Control of Emissions of RBSs Under Different Deployment Scenarios

Based on the researches, computer simulations and field measurement results in the representative locations, historical NIR levels in public-accessible areas in Hong Kong, and recommendations from Hong Kong MNOs, it is concluded that the control of emissions of RBSs for some deployment scenarios could be enhanced as summarized in Table 7-1.

Table 7-1: Summary of the feasibility for enhancing the control of emissions of RBSs under different deployment scenarios.

RBS Deployment Scenario	Relax / Tighten / Maintain the Controls on the Emissions of RBSs	Considerations
Rooftop RBSs	Relax	• Historical NIR levels in public-accessible areas due to emissions by rooftops RBSs are low • The time-averaged NIR level from RBSs that make use of mMIMO antennas with beamforming was within 1/8 to 1/5 of that of worst case NIR level of the RBS (estimated from measured reference signal) due to the technical behaviors of mMIMO beamforming
RBSs Installed on Street Furniture: Lamp Posts	Relax	• RBSs installed at high heights are similar to rooftops RBSs
RBSs Installed at External Wall of Buildings	Maintain	• RBS antennas could be in proximity to public-accessible areas
Indoor RBSs	Maintain	• RBS antennas could be in proximity to public-accessible areas
RBSs Installed on Street Furniture: Sheltered Bus Stop	Relax	• Computer simulations and field measurement results in representative locations show that ICNIRP safety limits can still be met when the transmitting power levels of the RBSs are increased
RBSs Installed on Street Furniture: Payphone Kiosks	Maintain	• No RBS has been installed on payphone kiosks in Hong Kong at the time of this study. The control of emission of RBSs installed on payphone kiosks should be further analyzed when there are more use cases of such deployment scenarios.

In the following, analyses and justifications are provided for the proposed enhancements on the control of emissions of RBSs.

RBSs that make use of mMIMO antennas

Based on market research (see Section 2.2 and Section 4) and field measurement results (see Section 6.3.2), for typical RBSs that make use of mMIMO antennas, the time-averaged NIR level from RBSs that made use of mMIMO antennas with beamforming was within 1/8 to 1/5 of the worst case NIR level from the RBS (estimated from measured reference signal) due to the technical behaviors of mMIMO beamforming. In other words, the maximum transmitting power for mMIMO antennas could be five times higher than that of conventional non-mMIMO antennas, while generating similar NIR levels in public-accessible areas.

Rooftop RBSs and RBSs installed at high heights on lamp posts

In Section 7.1, it is shown that historical NIR levels in Hong Kong due to emissions by RBSs deployed at rooftop level are low, which gives room for increasing the maximum transmitting power of such RBSs. At the same time, NIR levels are expected to increase as new frequency bands are introduced for the provision of mobile services in the 5G era and beyond. To accommodate these conditions while maintaining the NIR levels in Hong Kong on par with the historical low levels, past NIR measurements can be used to *extrapolate* NIR levels from RBSs based on Hong Kong's spectrum release plan for 2021 – 2023 and when more frequency bands are allocated in the future as follows:

$$\begin{pmatrix}\text{Predicted} \\ \text{NIR level} \\ \text{in the future}\end{pmatrix} = \left(\frac{\text{Maximum total emission level of an RBS site in the future}}{\text{Maximum total emission level of an RBS site in the past}}\right)\left(\begin{matrix}\text{Past NIR} \\ \text{Measurements}\end{matrix}\right)$$

$$= \left(\frac{\displaystyle\sum_{\substack{y\in\text{mobile} \\ \text{services} \\ \text{freq. bands} \\ \text{in the future}}}\left(\sum_{\substack{a\in\text{non-mMIMO} \\ \text{RBSs in} \\ \text{freq. band } y}}\left(P_{\text{tx},y,a}F_{\text{t2r},y,a}\right) + \sum_{\substack{b\in\text{mMIMO} \\ \text{RBSs in} \\ \text{freq. band } y}}\left(\bar{P}_{\text{tx},y,b}\bar{F}_{\text{t2r},y,b}F_{\text{rdn}}\right)\right)}{\displaystyle\sum_{\substack{y\in\text{mobile} \\ \text{services} \\ \text{freq. bands} \\ \text{in the past}}}\left(\sum_{\substack{a\in\text{non-mMIMO} \\ \text{RBSs in} \\ \text{freq. band } y}}\left(Q_{\text{tx},y,a}G_{\text{t2r},y,a}\right)\right)}\right)\left(\begin{matrix}\text{Past NIR} \\ \text{Measurements}\end{matrix}\right) \quad (7\text{-}1)$$

As shown in equation (7-1), the predicted NIR level in the future can be extrapolated by scaling the past NIR measurements with the ratio between the maximum total emission level of an RBS site in the future and the maximum total emission level of an RBS site in the past. The maximum total emission level of an RBS site in the future is given by the sum of the effective transmitting power of each RBS that makes use of conventional non-mMIMO antenna in each frequency band and the effective transmitting power of each RBS that makes use of mMIMO antenna in each frequency band; specifically,

- The effective transmitting power of each RBS that makes use of conventional non-mMIMO antenna in each frequency band is given by $\left\{\left\{P_{\text{tx},y,a}F_{\text{t2r},y,a}\right\}_{\substack{a\in\text{non-mMIMO} \\ \text{RBSs in} \\ \text{freq. band } y}}\right\}_{\substack{y\in\text{mobile} \\ \text{services} \\ \text{freq. bands} \\ \text{in the future}}}$, where $P_{\text{tx},y,a}$ is the transmitting power and $F_{\text{t2r},y,a}$ is the transmit-receive duty cycle; and

- The effective transmitting power of each RBS that makes use of mMIMO antenna in each frequency band is given by $\left\{\left\{\bar{P}_{\text{tx},y,b}\bar{F}_{\text{t2r},y,b}F_{\text{rdn}}\right\}_{\substack{b\in\text{non-mMIMO}\\ \text{RBSs in}\\ \text{freq. band } y}}\right\}_{\substack{y\in\text{mobile}\\ \text{services}\\ \text{freq. bands}\\ \text{in the future}}}$, where $\bar{P}_{\text{tx},y,b}$ is the transmitting power, $\bar{F}_{\text{t2r},y,b}$ is the transmit-receive duty cycle, and F_{rdn} is the power reduction factor when mMIMO antennas are used.

Since RBSs that make use of mMIMO antennas are deployed in Hong Kong after 2020, the maximum total emission level of an RBS site in the past is given by the sum of the transmitting power of each RBS that makes use of conventional non-mMIMO antenna in each frequency band, $\left\{\left\{Q_{\text{tx},y,a}G_{\text{t2r},y,a}\right\}_{\substack{a\in\text{non-mMIMO}\\ \text{RBSs in}\\ \text{freq. band } y}}\right\}_{\substack{y\in\text{mobile}\\ \text{services}\\ \text{freq. bands}\\ \text{in the past}}}$, where $Q_{\text{tx},y,a}$ is the transmitting power and $G_{\text{t2r},y,a}$ is the transmit-receive duty cycle.

Estimated NIR Levels with More Frequency Bands Allocated to Mobile Service in the Future

Prediction is made of ICNIRP compliance levels mainly attributed by outdoor RBS emissions at 700 MHz or above [44] based on Hong Kong's spectrum release plan for 2021 – 2023 extrapolated from street-level public-area measurements and measurements at sampled households in the vicinity of RBSs (i.e., household sites with potentially higher NIR level) conducted by OFCA in 2018, and the parameters are summarized in Table 7-2. It is assumed that some RBSs may make use of mMIMO antennas and their maximum transmitting power could be increased to accommodate the fact that NIR level contributed by mMIMO beamforming is limited to a certain fixed fraction of that of the RBS' maximum transmitting

[44] At the time of this study, the 700 MHz band is the lowest frequency band assigned for the provision of public mobile services. According to equation (2-4), the incident power density level corresponding to 700 MHz (see Table 2-3) is adopted for the calculation of the ICNIRP compliance level.

power. These results suggest that the NIR levels in public-accessible areas in Hong Kong will increase in the coming years if the maximum transmit power level of RBSs deployed at rooftop level is doubled. Nonetheless, the ICNIRP safety limits can still be met with some margins remained.

Table 7-2: Summary of parameters used for predicting the NIR levels from RBSs based on Hong Kong's spectrum release plan for 2021 – 2023.

	Year		
	2018	**2022**	**Hong Kong's Spectrum Release Plan for 2021 – 2023**
RBS Maximum Transmit Power Level†	w/o mMIMO antenna *P* W ERP with mMIMO antenna N/A	w/o mMIMO antenna 2*P*† W ERP with mMIMO antenna 2Q†† W ERP	w/o mMIMO antenna 2*P* W ERP with mMIMO antenna 2Q W ERP
Frequency Bands	• 850 MHz • 900 MHz • 1800 MHz • 2100 MHz • 2300 MHz • 2600 MHz	• 700 MHz • 850 MHz • 900 MHz • 1800 MHz • 2100 MHz • 2300 MHz • 2600 MHz • 3500 MHz • 4900 MHz • 26/28 GHz	• 700 MHz • 850 MHz • 900 MHz • 1800 MHz • 2100 MHz • 2300 MHz • 2600 MHz • 3500 MHz • 4900 MHz • 26/28 GHz • 39/43 GHz

† P W ERP is the maximum transmit power level of rooftop RBS with non-mMIMO antenna at the time of the study.

††Q W ERP is the maximum transmit power level of rooftop RBS with mMIMO antenna at the time of the study. The power reduction factor when mMIMO antennas are used is F_{rdn} = 5.

<u>RBSs installed on sheltered bus stops</u>

RBSs installed on sheltered bus stops are typically deployed to enhance service capacity. Such RBSs should be deployed with low EMF emission levels since 1) they are in close proximity to pedestrian walkways and vehicles on the road, and 2) a low EMF emission level could reduce mutual interference with nearby co-frequency RBSs (see Section 3.1). Based on international accepted guidelines (e.g., see **[Ref 4] [Ref 14]**) and field measurements results in representative locations in Hong Kong (see Section 6.3.3), control of emissions of RBSs at sheltered bus stops could be enhanced as follows:

- The transmitting power of RBSs operating at sub-6 GHz frequency range installed on sheltered bus stops with height equal to or greater than 3m can be increased from 2W ERP, if the antennas are not facing the road to avoid close proximity to vehicles on the road.

8 Routine Monitoring Mechanism on NIR in Public-Accessible Areas in Hong Kong

Since the environments in the vicinity of RBSs could change over time, an efficient and effective routine monitoring mechanism on NIR in public-accessible areas can allow OFCA to maintain updated NIR records and prevent any potential risks to the public in a timely fashion. This section presents the proposed routine monitoring mechanism on NIR in public-accessible areas suitable for adoption in Hong Kong addressing the following aspects:

- Reporting format and procedures for routine monitoring of NIR levels;
- Selection of appropriate locations for conducting NIR measurements;
- Recommendations for presenting NIR results for public consumption; and
- Feasibility of and candidate solutions for automated NIR monitoring.

8.1 Reporting Format and Procedures for Routine Monitoring of NIR Levels

8.1.1 Reporting Format of NIR Levels

The reporting format of NIR levels should provide the public with intuitive information about NIR safety. By the laws of physics (see equation (2-1)), the NIR level from RBS can be *equivalently* presented in terms of incident power density S_{inc} in Wm^{-2}, incident electric field strength E_{inc} in Vm^{-1}, or incident magnetic field strength H_{inc} in Am^{-1}. Traditionally, regulatory bodies worldwide report NIR levels from RBSs in terms of either incident power density or incident electric field strength, and these two formats are interconvertible. For ease of public consumption, it is intuitive to report NIR levels in terms of incident power density and the ICNIRP compliance level based on Broadband Measurements or Frequency-specific Measurements (see Section 2.1.1.2) due to the following considerations:

- The incident power density provides a straightforward representation of how much *power* is absorbed by the human body from one or more EMF sources as illustrated in Figure 8-1 **[Ref 1] [Ref 15]**.

- The ICNIRP compliance level represents the aggregate effect of all EMFs with respect to the NIR exposure restrictions.

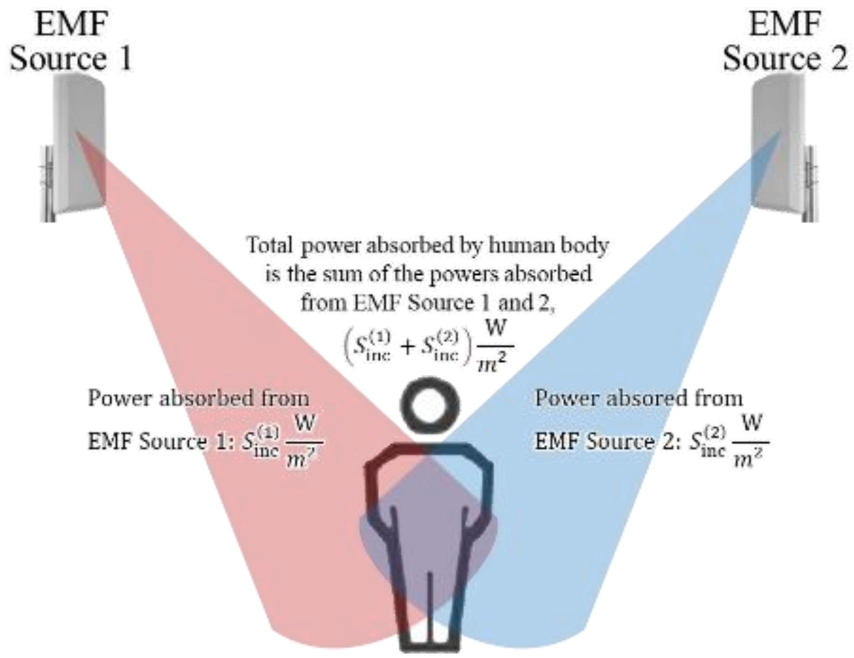


Figure 8-1: Illustration of the human body absorbing power from one or more EMF sources.

8.1.2 Procedures for Routine Monitoring of NIR Levels

Overall approach

The flow chart summarising the procedures for routine monitoring of NIR levels is shown in Figure 8-2. Specifically, NIR measurements should be conducted regularly cycling through a set of appropriate locations (see Section 8.2) and the measurement results should be published on a regular basis for public consumption. NIR measurements should be made during day time reflecting normal traffic conditions of mobile networks. At each measurement location, Broadband Measurements should be made for initially verification whether NIR levels are sufficiently low; if the broadband NIR level exceeds a certain threshold *Q*, Frequency-specific Measurements should be made to determine the dominant source(s) of NIR.

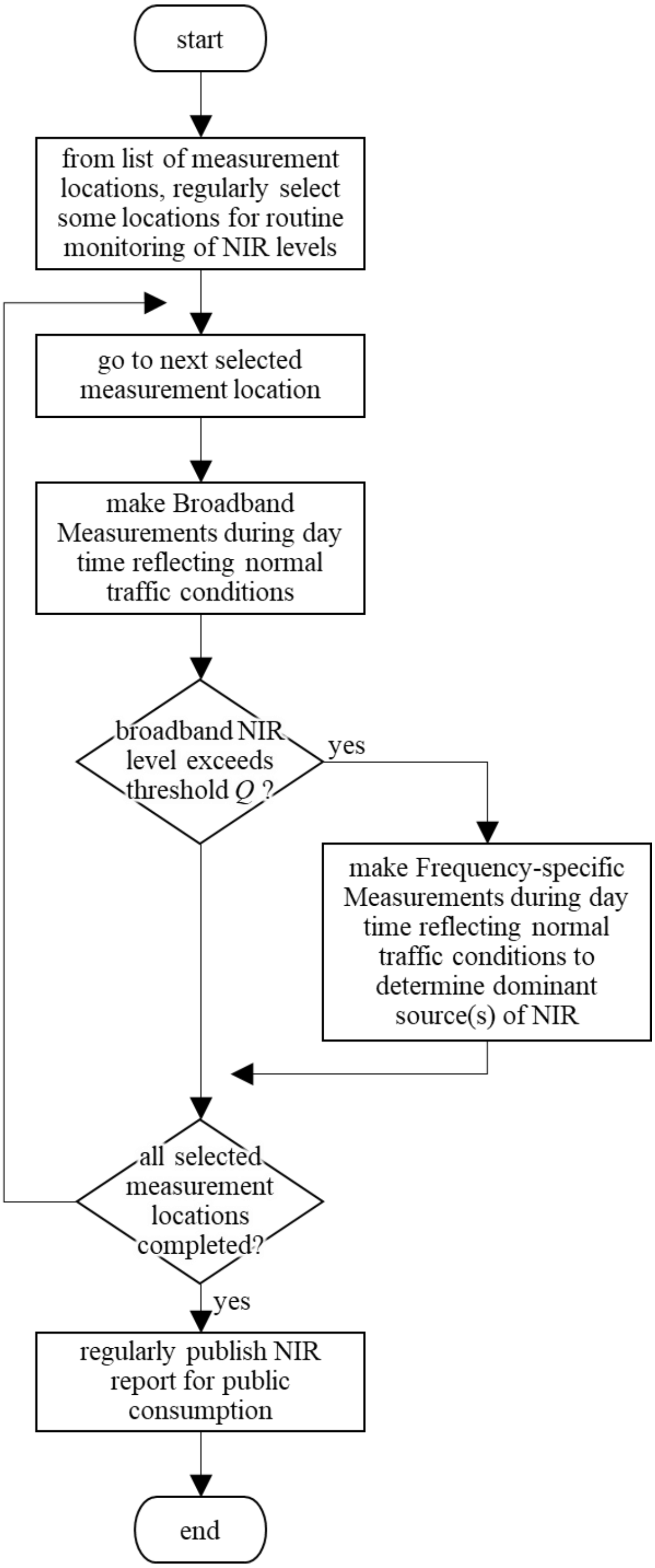


Figure 8-2: Flow chart of the procedures for routine monitoring of NIR levels.

Broadband NIR level threshold Q for the need to determine the dominant source(s) of NIR via Frequency-specific Measurements

Based on statistics of predicted NIR levels in public-accessible areas in Hong Kong, it is anticipated that in 2022 and beyond 95% of the Broadband Measurements should be below 30% of the ICNIRP compliance level, which is equivalent to an incident power density level of $1.05\ \mathrm{Wm}^{-2}$ mainly attributed by outdoor RBS emissions at 700 MHz or above[45] (see Section 7.2). If Broadband Measurement at a location shows that the NIR level exceeds the threshold $Q = 1.05\ \mathrm{Wm}^{-2}$, the NIR level is in the 95$^{\text{th}}$ percentile for NIR levels in public-accessible areas in Hong Kong, and it is appropriate to determine the dominant source(s) of NIR via Frequency-specific Measurements for exercising regulatory controls.

Measurement methodologies and data to be collected during Broadband and Frequency-specific Measurements

As of 2022, RBS deployment scenarios in Hong Kong include RBSs at rooftop, RBS installed at external wall of a building, RBSs installed on street furniture (such as payphone kiosks, sheltered bus stops and lamp posts), and indoor RBSs. Furthermore, RBSs may employ FDD or TDD modes of operation and the RBSs may make use of mMIMO antennas or conventional non-mMIMO antennas. Without loss of generality, the *same* measurement methodologies could be employed for all RBS deployment scenarios and technologies since routine monitoring of the NIR level reflecting normal traffic conditions of mobile networks only

[45] As of the first quarter of 2022, the 700 MHz band is the lowest frequency band assigned for the provision of public mobile services. The incident power density reference level corresponding to 700 MHz is adopted for the calculation of the ICNIRP compliance level (see Table 2-3 and equation (2-4)), i.e., the ICNIRP compliance level is given by $\left(\frac{\text{Total Incident Power Density}}{3.5\ \mathrm{W/m^2}}\right)(100\%)$.

depends on the emission levels of each RBS on each frequency band and the total of number frequency bands being used.

At a given measurement location, measurement points should be selected with the following considerations **[Ref 4]**.

- Position: The measurement point should be at a position with frequent public gathering or high pedestrian flow to reflect the public's NIR exposure level or at a position in the vicinity of RBS antennas with potentially higher NIR level.
- Height above ground: Measurements should be made between 1.5m to 2.0m above ground at similar heights as the vital organs of the human body, i.e., the head.

Broadband Measurements should be made using a broadband power meter and probe, whereas Frequency-specific Measurements should be made using a spectrum analyzer[46]. Since NIR levels fluctuate due to instantaneous environment changes, NIR levels should be measured in terms of the *maximum average*[47] (i.e., the maximum value of the running-average NIR level averaged over the measurement interval) to obtain a bound on the typical NIR level. The assessment form for routine monitoring of NIR levels from RBSs is provided in Annex J.

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[46] See Section 6.3.1 for an introduction of NIR measurement equipment.

[47] Most NIR measurement equipment support taking *maximum average* measurements as a built-in feature.

8.2 Selection of Appropriate Locations for Conducting NIR Measurements and Recommendations for Presenting NIR Results for Public Consumption

Routine monitoring of NIR levels from RBSs at appropriate locations within a region allows a regulatory body to maintain updated NIR records and prevent any potential risks to the public in a timely fashion, whereas regular and transparent disclosure of NIR levels at public areas can help alleviate public concerns. Therefore, the locations for conducting NIR measurements should be selected to holistically include areas with potentially high NIR level or to draw public attention as described below.

- Areas with higher density of RBSs in the vicinity: NIR level is contributed by the emission levels of individual RBS in the vicinity operating on the respective frequency bands and contingent upon the number of frequency bands being used. In this connection, areas with higher density of RBSs in the vicinity would potentially have higher NIR levels.
- Crowded areas with frequent public gathering or high pedestrian flow: NIR level increases with the increasing traffic load of the mobile networks. In this connection, crowded areas with frequent public gathering or high pedestrian flow would potentially have higher NIR levels which may impact a large number of people.

As part of this study, based on the distribution of RBSs in Hong Kong and site survey, some recommended locations for routine monitoring of NIR levels in Hong Kong are identified and shown on the map of Hong Kong in Figure 8-3.

Figure 8-3: Recommended locations for routine monitoring of NIR levels shown on the map of Hong Kong with sample NIR measurement data collected in 2022.

8.3 Feasibility of and Candidate Solutions for Automated NIR Monitoring

Region-wide NIR monitoring involves a large number of measurement locations, where conventional manual measurement approaches require significant time and human resources. Based on market research and recommendations from test and measurement equipment vendors, as of 2022, there are solutions available for automated NIR monitoring as illustrated in Figure 8-4. Specifically, broadband and frequency-specific power sensors with network connectivity are available in the market which could be deployed at measurement locations for remotely collecting NIR measurements via cloud-based approaches. On one hand, automated NIR monitoring offers the advantage of continuous NIR monitoring at key measurement locations towards reducing the time and human resources required for conventional manual measurement. On the other hand, automated NIR monitoring has the disadvantage that an extensive infrastructure needs to be set up including the deployment of power sensors at the measurement locations and establishment of network connectivity. Moreover, additional investments are required to maintain the power sensors or relocate the power sensors to other measurement locations as the environment may change over time.

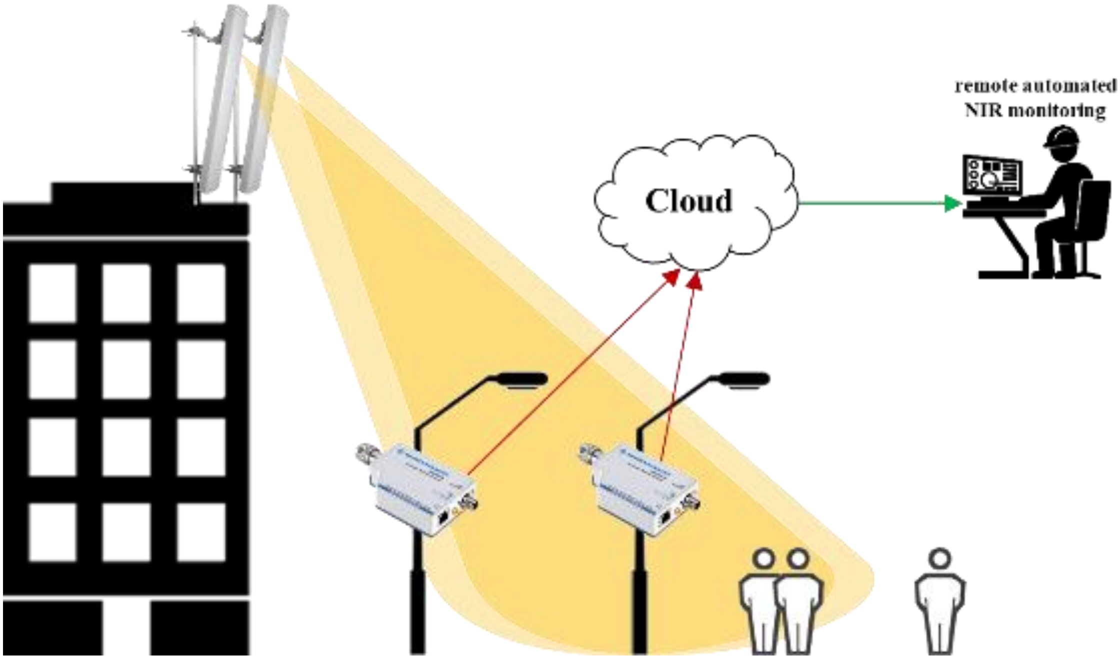

Figure 8-4: System model for automated NIR monitoring solution.

9 Conclusions

This report assessed in details the technical matters in relation to NIR from RBSs, the typical NIR exposure level of Hong Kong, and practical measures to ensure radiation safety of RBSs. The feasibility for enhancing the control of emissions of RBSs under different deployment scenarios was also examined. The findings were based on technical studies, technical exchanges with Hong Kong MNOs and RBS equipment vendors, theoretical analysis, computer simulations, and field measurements for investigating various RBS deployment scenarios including RBSs installed at roof top locations, at indoor locations, on street furniture (such as payphone kiosks, sheltered bus stops and lamp posts), and at external wall of buildings. The key conclusions as drawn from the findings of Sections 2 – 8 of this report are described in the succeeding paragraphs.

Assessments and Enhancements on Existing Regulatory Measures on NIR Safety of RBSs Adopted by Hong Kong

- Hong Kong adopts the ICNIRP safety limits in establishing the regulatory measures for ensuring the radiation safety of RBSs. OFCA employs the mechanisms for NIR measurements and monitoring on par with that of other regulatory bodies worldwide. To enhance Hong Kong public's awareness and confidence in NIR safety of RBSs, OFCA can publish with discretion the NIR measurement results of public areas.

New Regulatory Measures That Could Be Adopted by Hong Kong

- Assessment models and computer simulation tools drawing reference to relevant technical documents and recommendations issued by international organizations and standardization bodies were developed for evaluating NIR levels from RBSs to support OFCA with exercising regulatory controls (such as assessing the feasibility of bringing new RBSs into operation or adjusting the transmitting power of existing

RBSs in the vicinity to ensure that the aggregate NIR continue to be in compliant with the ICNIRP safety limit).

- A routine monitoring mechanism on NIR in public-accessible areas in Hong Kong was proposed. It is recommended that OFCA should routinely monitor NIR levels in public-accessible areas by conducting NIR measurements regularly at appropriate locations (i.e., areas with higher density of RBSs in the vicinity, crowded areas with frequent public gathering or high pedestrian flow, etc.) and publish the measurement results on a regular basis for public consumption. At each measurement location, Broadband Measurements should be made for initially verification whether NIR levels are sufficiently low; if the broadband NIR level exceeds 30% of the ICNIRP compliance level, Frequency-specific Measurements should be made to determine the dominant source(s) of NIR. At the time of this study, automated NIR monitoring is not practically feasible as it requires the setting up of an extensive infrastructure that is costly to maintain or modify.

Typical NIR Exposure Level of Hong Kong

- The NIR levels in public-accessible areas in Hong Kong are historically well below the ICNIRP safety limits. Based on OFCA's past records on street-level public-area measurements and measurements at sampled households in the vicinity of RBSs (i.e., household sites with potentially higher NIR level), at least 95% of the street-level public area measurements were below 5% of the ICNIRP compliance level and 95% of the measurements at sampled households in the vicinity of RBSs were below 10% of the ICNIRP compliance level.

Field Measurements on NIR Levels in Representative Locations

- Based on the researches, site surveys, and recommendations from Hong Kong MNOs, ten RBS deployment sites have been selected for NIR level assessment and for drawing different observations. At each site, both Broadband Measurements and Frequency-specific Measurements were conducted. Computer simulations and field measurements on the NIR levels from RBSs at these ten representative locations in Hong Kong in 2021 to 2022 showed that the NIR levels are below 5% of the ICNIRP safety limits.

NIR Safety Due to the Use of New Radio Technologies

- Field measurement results showed that the time-averaged NIR level from RBSs that make use of mMIMO antennas in Hong Kong is typically 1/8 to 1/5 of the worst case NIR level from the RBS (estimated from measured reference signal) due to the technical behaviors of mMIMO beamforming.

Recommendations on Regulatory Control on Emissions of RBSs

- Regulatory controls on the emissions of RBSs could be enhanced. Using past NIR measurements to *extrapolate* NIR levels in 2022 and beyond, it was identified that emissions from RBSs at rooftop and RBSs installed at high heights on lamp posts could be increased with the NIR levels in public-accessible areas still being maintained on par with the historical low levels. Emissions by RBSs installed on sheltered bus stops could be increased but the total radiated power of all co-located RBSs should remain at low levels since these RBSs are typically deployed to support local hotspots. In other words, an MNO can install one or more RBSs on the same sheltered bus stop with different radiated power for supporting its mobile services as long as the limit on the stipulated total radiated power can be met.

9.1 Limitations of the Study

In hindsight, there were several limitations of this consultancy study posed by the technical specifications of 5G RBSs available in the market.

First, at the time of study, RBSs that make use of mMIMO antenna transmit signals using dynamically-selected radiation patterns chosen based on the vendor-specific algorithms. The number of radiation patterns supported by the mMIMO antennas and the technical specifications (e.g., gain, beamwidth, etc.) of each radiation pattern depend on the number of radiating elements built into the mMIMO antenna and is subject to vendor specific design. Therefore, this study could only verify via field measurements that the time-averaged NIR level of mMIMO antennas in Hong Kong is typically 1/8 to 1/5 of the worst case NIR level from the RBS (estimated from measured reference signal) due to the technical behaviors of mMIMO beamforming.

Secondly, at the time of this study, mmWave RBSs available in the market all use mMIMO antennas with relatively large physical dimensions, and they are typically deployed in outdoor environments or high above ground in indoor environments. Therefore, no measurement was conducted on NIR levels from low power indoor mmWave RBSs that make use of conventional non-mMIMO antennas.

9.2 Prospect and Further Study

This study report examined NIR safety of RBSs in Hong Kong covering all representative RBS deployment scenarios and state-of-the art RBS technologies. As RBS technologies continue to evolve, OFCA should conduct further studies on 1) the technical behaviors of mMIMO beamforming of next generation mMIMO antennas and 2) the NIR levels generated from low power indoor mmWave RBSs that make use of conventional non-mMIMO antennas.

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Annex A Hong Kong's Spectrum Release Plan for the Provision of Public Mobile Services and Wireless Broadband Services

Table A-1 summarizes the existing and planned frequency bands for the provision of public mobile services and wireless broadband services in Hong Kong[48]. Note that some frequency bands are assigned in pairs.

Table A-1: Summary of existing and planned frequency bands for the provision of public mobile services and wireless broadband services in Hong Kong.

Frequency Band (MHz)	Remarks
617 – 652 663 – 698	• Planned for provision of public mobile services • Restricted to indoor use only
703 – 738 758 – 793	• Assigned for provision of public mobile services
825.0 – 832.5 870.0 – 877.5	• Assigned for provision of public mobile services
885 – 915 930 – 960	• Assigned for provision of public mobile services
1710 – 1785 1805 – 1880	• Assigned for provision of public mobile services
1920.3 – 1979.7 2110.3 – 2169.7	• Assigned for provision of public mobile services
2300 – 2390	• Assigned for provision of public mobile services
2500 – 2570 2620 – 2690	• Assigned for provision of public mobile services
3300 – 3400	• Assigned for provision of public mobile services • Restricted to indoor use only
3400 – 3600	• Assigned for provision of public mobile services
4800 – 4960	• Assigned for provision of public mobile services
24250 – 27950	• Assigned for provision of large scale public mobile services
27950 – 28350	• Allocated for Localized Wireless Broadband Services
39500 – 43500	• Planned for the provision of mobile / wireless fixed services

[48] See https://www.ofca.gov.hk/filemanager/ofca/common/Industry/broadcasting/spectrum_plan2021_en.pdf and https://www.ofca.gov.hk/filemanager/ofca/common/Industry/broadcasting/hk_freq_table_en.pdf.

Annex B Dimensions of Antennas Typically Used in Different RBS Deployment Scenarios

Based on market research in 2022, the dimensions of antennas typically used in different RBS deployment scenarios in Hong Kong are listed in Table B-1. As of 2022, RBSs that operate at the 3500 MHz, 4900 MHz, and 28 GHz frequency bands make use of mMIMO antennas, and RBSs that operate at the 4900 MHz and 28 GHz bands always use mMIMO antennas. Since an mMIMO antenna includes electronic and heat dissipation components in addition to an array of radiating elements, the physical dimensions of an mMIMO antenna are larger than the array of radiating elements, whose longest dimension is typically less than 10λ.

Table B-1: Dimensions of antennas typically used in different RBS deployment scenarios in Hong Kong in 2022 and the approximate boundary for EMF far-field zone.

RBS Deployment Scenario	Frequency Band	Longest Dimension of Antenna, D	Approximate Inner Boundary for EMF Far-Field Zone, $2D^2/\lambda$
Rooftop RBSs	850 MHz ($\lambda = 0.353$m)	1.5m	12.75m
	900 MHz ($\lambda = 0.333$m)		13.50m
	1800 MHz ($\lambda = 0.167$m)		27.00m
	2100 MHz ($\lambda = 0.143$m)		31.50m
	2300 MHz ($\lambda = 0.130$m)		34.50m
	2600 MHz ($\lambda = 0.115$m)		39.00m
	3300 MHz ($\lambda = 0.091$m)		49.50m
	3500 MHz ($\lambda = 0.086$m)		52.50m
	4900 MHz ($\lambda = 0.061$m)	$\min(10\lambda, 1.5\text{m})$	12.20m
	28 GHz ($\lambda = 0.011$m)	$\min(10\lambda, 0.5\text{m})$	2.14m
RBS installed at external wall of buildings	850 MHz ($\lambda = 0.353$m)	1.0m	5.67m
	900 MHz ($\lambda = 0.333$m)		6.00m
	1800 MHz ($\lambda = 0.167$m)		12.00m
	2100 MHz ($\lambda = 0.143$m)		14.00m
	2300 MHz ($\lambda = 0.130$m)		15.33m
	2600 MHz ($\lambda = 0.115$m)		17.33m
	3300 MHz ($\lambda = 0.091$m)		22.00m
	3500 MHz ($\lambda = 0.086$m)		23.33m
	4900 MHz ($\lambda = 0.061$m)	$\min(10\lambda, 1.0\text{m})$	12.20m
	28 GHz ($\lambda = 0.011$m)	$\min(10\lambda, 0.5\text{m})$	2.14m
RBSs installed on street furniture	850 MHz ($\lambda = 0.353$m)	0.25 – 0.5m	0.35 – 1.42m
	900 MHz ($\lambda = 0.333$m)		0.38 – 1.50m
	1800 MHz ($\lambda = 0.167$m)		0.75 – 3.00m
	2100 MHz ($\lambda = 0.143$m)		0.88 – 3.50m
	2300 MHz ($\lambda = 0.130$m)		0.96 – 3.83m
Indoor RBSs	2600 MHz ($\lambda = 0.115$m)		1.08 – 4.33m
	3300 MHz ($\lambda = 0.091$m)		1.38 – 5.50m
	3500 MHz ($\lambda = 0.086$m)		1.46 – 5.83m
	4900 MHz ($\lambda = 0.061$m)		2.04 – 8.17m
	28 GHz ($\lambda = 0.011$m)	$\min(10\lambda, 0.5\text{m})$	2.14m

Annex C Simulated Radiation Patterns of an Antenna at Different Distances From an Antenna

The radiation pattern of an antenna is established from the constructive interference of EMFs emitted by the radiating elements of the antenna (see **[Ref 16]** and references therein). Consider an antenna whose longest dimension is D meters and transmits signals with wavelength λ. In general, the designed radiation pattern of an antenna is established in the far-field zone of the EMF (i.e., at distances $R \geq 2D^2/\lambda$ meters from the antenna). For illustration, Figure C-1 shows the simulated radiation patterns of an antenna whose longest dimension is $D = 3.7\lambda$ meters at distances of 2λ, 4λ, 8λ, 16λ, 28λ, and 32λ meters from the antenna. It can be observed from Figure C-1 that 1) the radiation pattern stabilizes in the far-field zone of the EMF beyond $28\lambda \approx 2(3.7\lambda)^2/\lambda$ meters from the antenna and 2) the antenna gain in the radiative near-field of the EMF is generally lower than the expected antenna gain.

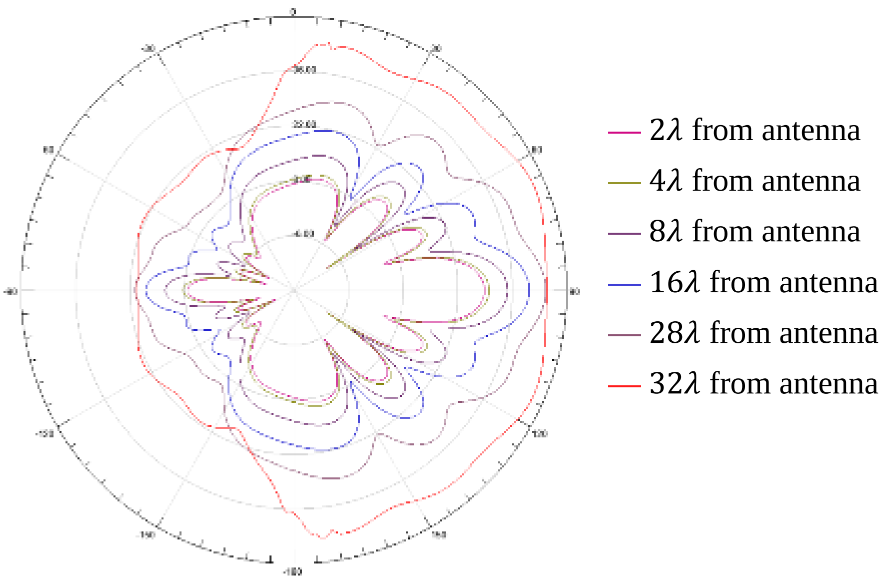


Figure C-1: Simulated radiation patterns of an antenna at different distances from an antenna.

Annex D Introduction to 4G and 5G RBS Reference Signals, Data Signals, and mMIMO Beamforming

Signals transmitted by RBSs include *reference signals* and *data signals* as illustrated in Figure D-1. Reference signals are broadcast by RBSs using a small fraction of frequency-temporal resources (or dedicated codes) to allow terminals to 1) discover nearby cells, 2) synchronize to nearby cells, and 3) measure the signal quality of nearby cells to facilitate cell selection for attachment and handover between cells. Data signals are transmitted as needed by RBSs to deliver data to each terminal.

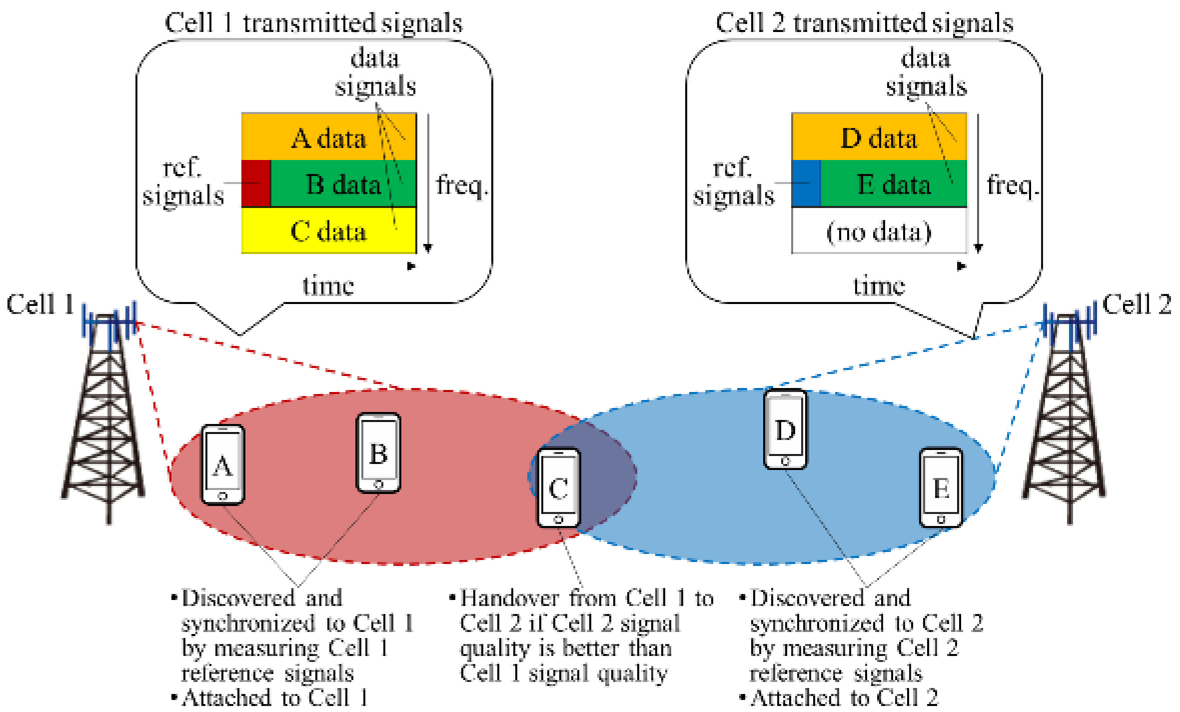
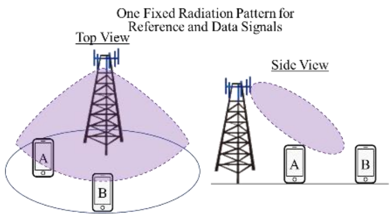
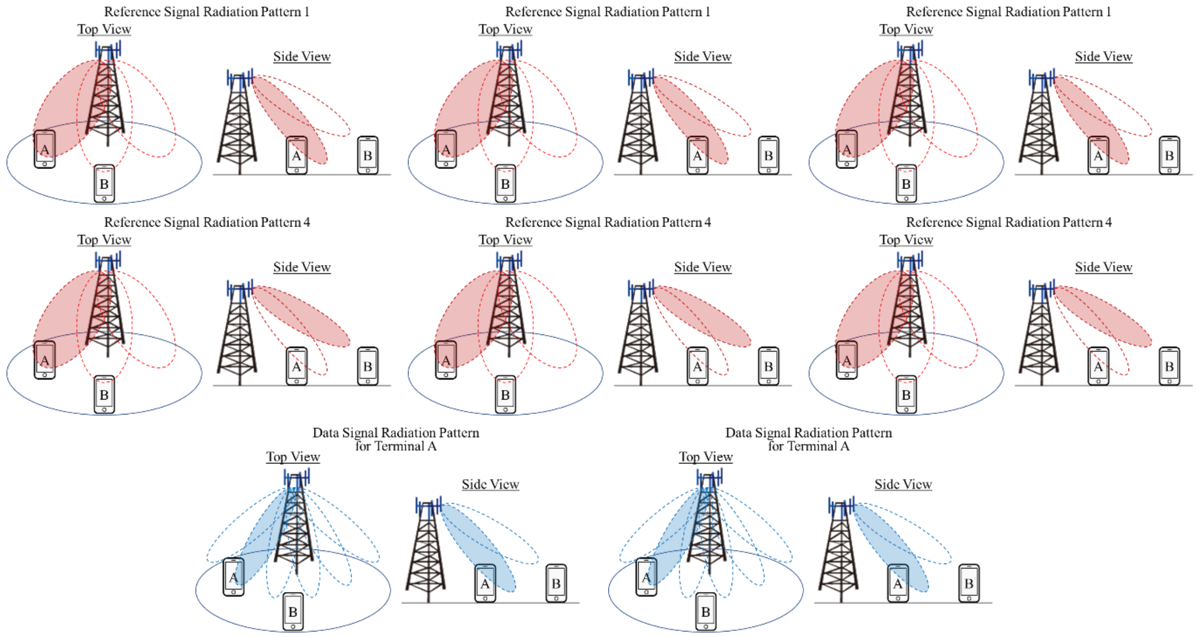


Figure D-1: Illustration of 4G and 5G RBS transmitted signals including reference signals and data signals.

In the 5G era, RBSs may make use of mMIMO antennas. According to market research and 4G and 5G RBSs standard specifications in 2022, an RBS that makes use of conventional non-mMIMO antenna transmits its signals using a fixed radiation pattern (see Figure D-2a), whereas an RBS that makes use of mMIMO antenna transmits reference signals and data signals using different radiation patterns (see Figure D-2b). Moreover, an RBS that makes use of mMIMO antenna periodically transmits reference signals using different radiation patterns such that terminals in different directions may receive the reference signals, and it transmits data signals to the targeted terminals using a radiation pattern chosen based on vendor-specific algorithms. The number of radiation patterns supported by an mMIMO antenna and the technical specifications (e.g., gain, beamwidth, etc.) of each radiation pattern depend on the number of radiating elements built into the mMIMO antenna and subject to vendor specific design.



(a)



(b)

Figure D-2: Illustration of signal transmission by an RBS (a) using conventional non-mMIMO antenna and (b) using mMIMO antenna.

Modeling the RBS operations described above and treating each signal as a separate EMF source, for a 4G or 5G RBS with a maximum transmit power level P_{tx}, the EIRP during a scheduling interval[49] T_{sch} towards azimuth angle θ and elevation angle ϕ can be approximated as **[Ref 6] [Ref 7] [Ref 9]**

$$\begin{aligned}\text{EIRP}(\theta, \phi, P_{\text{tx}}, T_{\text{sch}}) &= F_{\text{rdn,ref}} P_{\text{tx}} \, B_{\text{ant,ref}}(\theta, \phi, T_{\text{sch}}) G_{\text{ant,ref}} \\ &+ \sum_{\substack{x \in \text{terminals receiving} \\ \text{data in this } T_{\text{sch}}}} \{(F_{\text{rdn},x} P_{\text{tx}} \, B_{\text{ant},x}(\theta, \phi, T_{\text{sch}}) G_{\text{ant},x})\},\end{aligned} \tag{D-1}$$

where

1) $0 < F_{\text{rdn,ref}} \leq 1$ is a power reduction factor to model the fraction of the total transmit power used for transmitting reference signals;

2) $0 < F_{\text{rdn},x} \leq 1$ is a power reduction factor to model the fraction of the total transmit power used for transmitting data signal to terminal *x*;

3) $$F_{\text{rdn,ref}} + \sum_{\substack{x \in \text{terminals receiving} \\ \text{data in this } T_{\text{sch}}}} F_{\text{rdn},x} \leq 1 \; ;$$

4) $G_{\text{ant,ref}}$ is the maximum antenna gain in the main lobe of the radiation pattern used for transmitting reference signals;

5) $0 < B_{\text{ant,ref}}(\theta, \phi, T_{\text{sch}}) \leq 1$ is a function modeling the normalized radiation pattern averaged over time T_{sch} used for transmitting reference signals;

[49] A scheduling interval refers to the minimum time duration in which a specific group of terminals are scheduled to receive data from the RBS simultaneously.

6) $G_{\text{ant},x}$ is the maximum antenna gain in the main lobe of the radiation pattern used for transmitting data signal to terminal *x*; and

7) $0 < B_{\text{ant},x}(\theta, \phi, T_{\text{sch}}) \leq 1$ is a function modeling the normalized radiation pattern averaged over time T_{sch} used for transmitting data signal to terminal *x*.

Equation (D-1) helps to draw the following observations:

- For an RBS that makes use of mMIMO antenna, the level of EMF emitted by an RBS towards a given direction could be affected by traffic load and mMIMO beamforming. The EIRP towards a given direction is maximized 1) under maximum traffic loads (i.e., the RBS uses all available transmit powers to transmit data signals) and 2) the same radiation pattern is used for transmitting data signals to all terminals (e.g., when all the terminals are concentrated in an area). On the contrary, the EIRP towards a given direction would be substantially lowered 1) under low traffic loads and 2) this direction is outside of the main lobe of the radiation pattern(s) used for transmitting data signal(s) (e.g., no terminal in this direction is receiving data).

- For an RBS that makes use of conventional non-mMIMO antenna, it transmits radio signals using a fixed radiation pattern. The EIRP towards a given direction is maximized under maximum traffic loads (i.e., the RBS uses all available transmit powers to transmit data signals) but is not affected by the locations of the terminals since a fixed radiation pattern is used.

Annex E Methodology and Analytical Model for Estimating the Total NIR Level of a Target RBS Based on Reference Signal Measurement

As discussed in Section 2.1.2.2 and Annex D, RBSs transmit reference signals and it is feasible to estimate the total NIR level of a target RBS based on reference signal measurements. Specifically, consider an RBS that transmits signals at frequency f with wavelength λ. As illustrated in Figure E-1, the reference signal power at a given location for this RBS can be measured with equipment such as a signal analyzer or a network scanner that are commonly used by regulatory bodies and MNOs. On one hand, an RBS that uses conventional non-mMIMO antenna transmits reference signals and data signals using a fixed radiation pattern (see Figure E-1a). Since the fraction of the total RBS transmit power used for transmitting reference signals is known (i.e., based on the technology standard), it is feasible to *extrapolate* the *worst case* received power under maximum traffic load from the reference signal power measurements. On the other hand, an RBS that uses mMIMO antenna may dynamically transmit reference signals and data signals using different radiation patterns (see Figure E-1b). Since the fraction of the total RBS transmit power used for transmitting reference signals is known (i.e., based on technology standard and system configurations), it is feasible to *extrapolate* the *worst case* received power by modeling the scenario when a data signal beam is pointing towards this location with maximum traffic load.

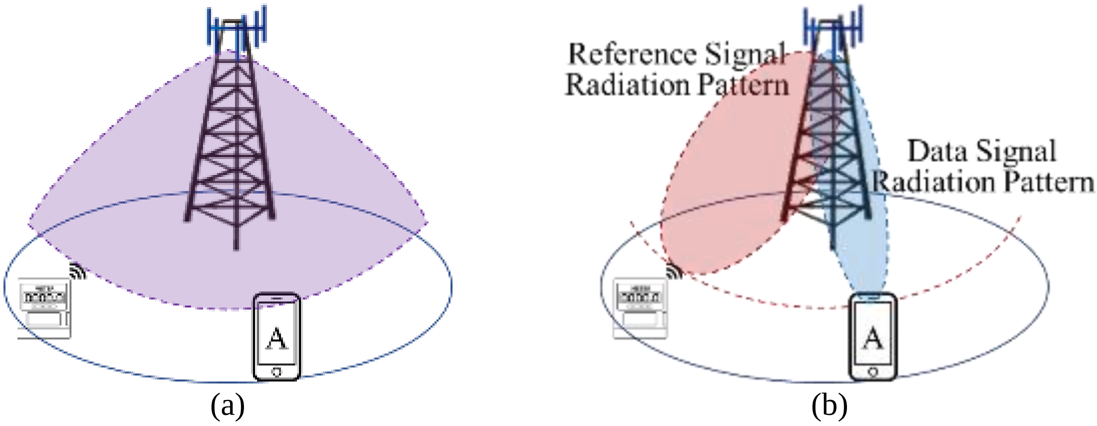


Figure E-1: Illustration of measuring reference signal power for an RBS (a) using conventional non-mMIMO antenna and (b) using mMIMO antenna.

Based on the reference signal power at a given location, the incident power density in Wm^{-2} can be estimated as follows:

$$S_{\text{inc}} = \frac{4\pi}{\lambda^2} F_{\text{total2ref}} 10^{\frac{P_{\text{ref}} - 30 - G_{\text{ant,rx}}}{10}}, \quad \text{(E-1)}$$

where

1) $F_{\text{total2Ref}}$ is a factor to model the ratio between the total RBS signal power and the reference signal power;

2) P_{ref} is the reference signal power in dBm; and

3) $G_{\text{ant,rx}}$ is the receive antenna gain in dBi.

Different RBS technologies have different specifications for the ratio between the reference signal power and the total RBS signal power, where the values for 3G to 5G systems using different frequencies and bandwidth configurations are summarized in Table E-1.

Table E-1: Summary of reference signal types for different RBS technologies and the ratio between total RBS signal power and the reference signal power for typical configurations used in Hong Kong.

RBS Technology	Reference Signal Type	Frequency Range	Bandwidth (MHz)	Ratio Between Total RBS Signal Power $F_{\text{total2ref}}$ and Reference Signal Power
3G	Primary Common Pilot Channel (P-CPICH)[50]	Below 3 GHz	5	10
4G	Reference Signal Received Power ("RSRP")	Below 3 GHz	5	300
			10	600
			15	900
			20	1200
5G	RSRP	Below 3 GHz (15 kHz subcarrier spacing)	5	300
			10	624
			15	948
			20	1272
		3 to 6 GHz (30 kHz subcarrier spacing)	30	936
			40	1272
			50	1596
			60	1944
			80	2604
		mmWave (120 kHz subcarrier spacing)	100	792
			200	1584

50 See https://www.narda-sts.com/de/produkte/selektiv-emf/srm-3006-field-strength-analyzer/pd/pdfs/22727/eID/.

Annex F NIR Reference Levels Defined in the ICNIRP 2020 Guidelines and the ICNIRP 1998 Guidelines

Table F-1: Whole-body average reference levels for NIR exposure averaged over a 30-minute interval defined in the ICNIRP 2020 guidelines.

Exposure Scenario	Frequency Range	Reference Levels (expressed as root mean square values)			RBS Frequency Band
		Incident Electric Field Strength $E_{\mathrm{inc,RL}}(\mathrm{Vm}^{-1})$	Incident Magnetic Field Strength $H_{\mathrm{inc,RL}}(\mathrm{Am}^{-1})$	Incident Power Density $S_{\mathrm{inc,RL}}(\mathrm{Wm}^{-2})$	
Occupational	$0.1 \leq f \leq 30$ MHz	$660/f^{0.7}$	$4.9/f$	N/A	No
	$30 < f \leq 400$ MHz	61	0.16	10	No
	$400 < f \leq 2000$ MHz	$3f^{0.5}$	$0.008f^{0.5}$	$f/40$	Yes
	$2 < f \leq 300$ GHz	N/A	N/A	50	Yes
General Public	$0.1 \leq f \leq 30$ MHz	$300/f^{0.7}$	$2.2/f$	N/A	No
	$30 < f \leq 400$ MHz	27.7	0.073	2	No
	$400 < f \leq 2000$ MHz	$1.375f^{0.5}$	$0.0037f^{0.5}$	$f/200$	Yes
	$2 < f \leq 300$ GHz	N/A	N/A	10	Yes

Table F-2: Whole-body average reference levels for NIR exposure averaged over a 6-minute interval in the ICNIRP 1998 guidelines.

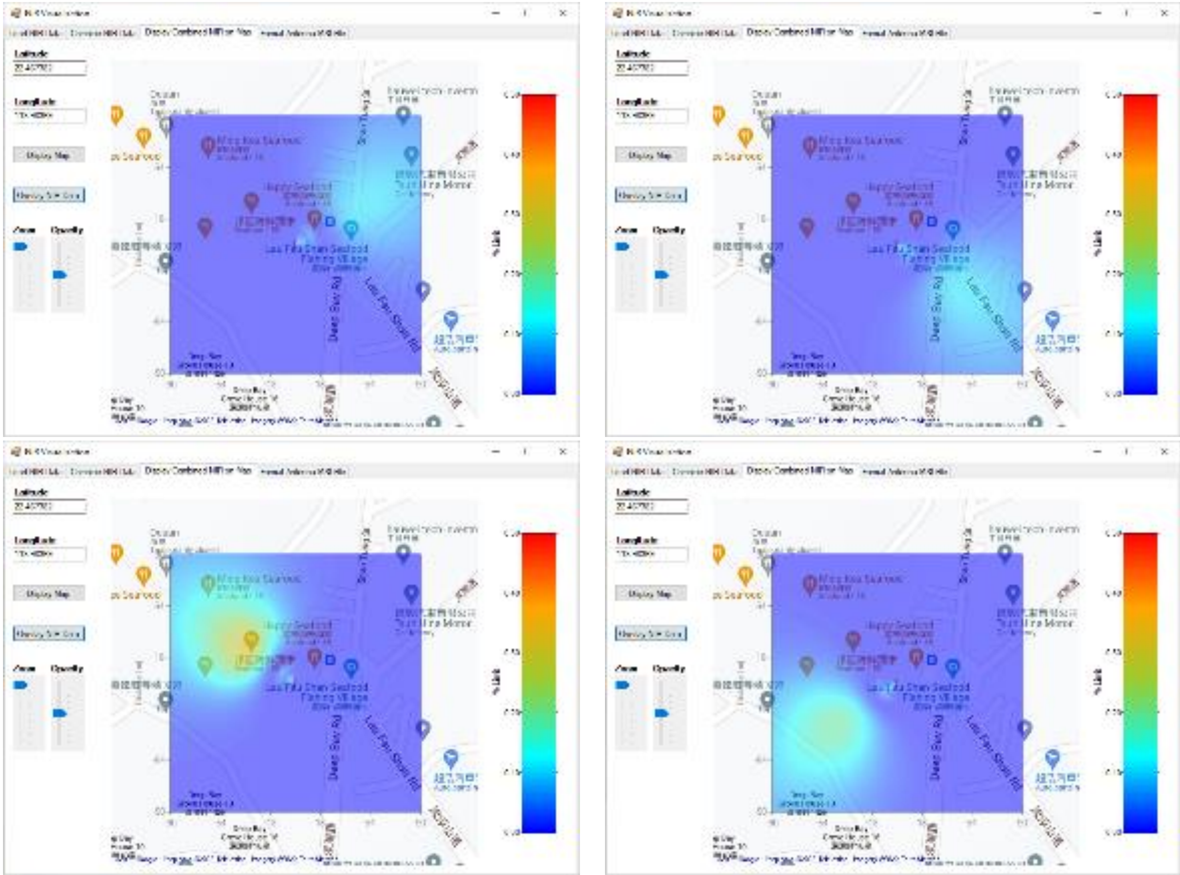
Exposure Scenario	Frequency Range	Reference Levels (expressed as root mean square values)			RBS Frequency Band
		Incident Electric Field Strength $E_{\mathrm{inc,RL}}(\mathrm{Vm}^{-1})$	Incident Magnetic Field Strength $H_{\mathrm{inc,RL}}(\mathrm{Am}^{-1})$	Incident Power Density $S_{\mathrm{inc,RL}}(\mathrm{Wm}^{-2})$	
Occupational	$f \leq 1$ Hz	N/A	163,000	N/A	No
	$1 < f \leq 8$ Hz	20,000	$163{,}000/f^2$	N/A	No
	$8 < f \leq 25$ Hz	20,000	$20{,}000/f$	N/A	No
	$0.025 < f \leq 0.82$ kHz	$500/f$	$20/f$	N/A	No
	$0.82 < f \leq 65$ kHz	610	24.4	N/A	No
	$0.065 < f \leq 1$ MHz	610	$1.6/f$	N/A	No
	$1 < f \leq 10$ MHz	$610/f$	$1.6/f$	N/A	No
	$10 < f \leq 400$ MHz	61	0.16	10	No
	$400 < f \leq 2000$ MHz	$3f^{0.5}$	$0.008f^{0.5}$	$f/40$	Yes
	$2 < f \leq 300$ GHz	137	0.36	50	Yes
General Public	$f \leq 1$ Hz	N/A	32,000	N/A	No
	$1 < f \leq 8$ Hz	10,000	$32{,}000/f^2$	N/A	No
	$8 < f \leq 25$ Hz	10,000	$4{,}000/f$	N/A	No
	$0.025 < f \leq 0.8$ kHz	$250/f$	$4/f$	N/A	No
	$0.8 < f \leq 3$ kHz	$250/f$	5	N/A	No
	$3 < f \leq 150$ kHz	87	5	N/A	No
	$0.15 < f \leq 1$ MHz	87	$0.73/f$	N/A	No
	$1 < f \leq 10$ MHz	$87/f^{0.5}$	$0.73/f$	N/A	No
	$10 < f \leq 400$ MHz	28	0.073	2	No
	$400 < f \leq 2000$ MHz	$1.375f^{0.5}$	$0.0037f^{0.5}$	$f/200$	Yes
	$2 < f \leq 300$ GHz	61	0.16	10	Yes

Annex G Implementation of Analytical Models for Predicting NIR Levels From a Single or Multiple RBSs Operating in One or More Frequency Bands

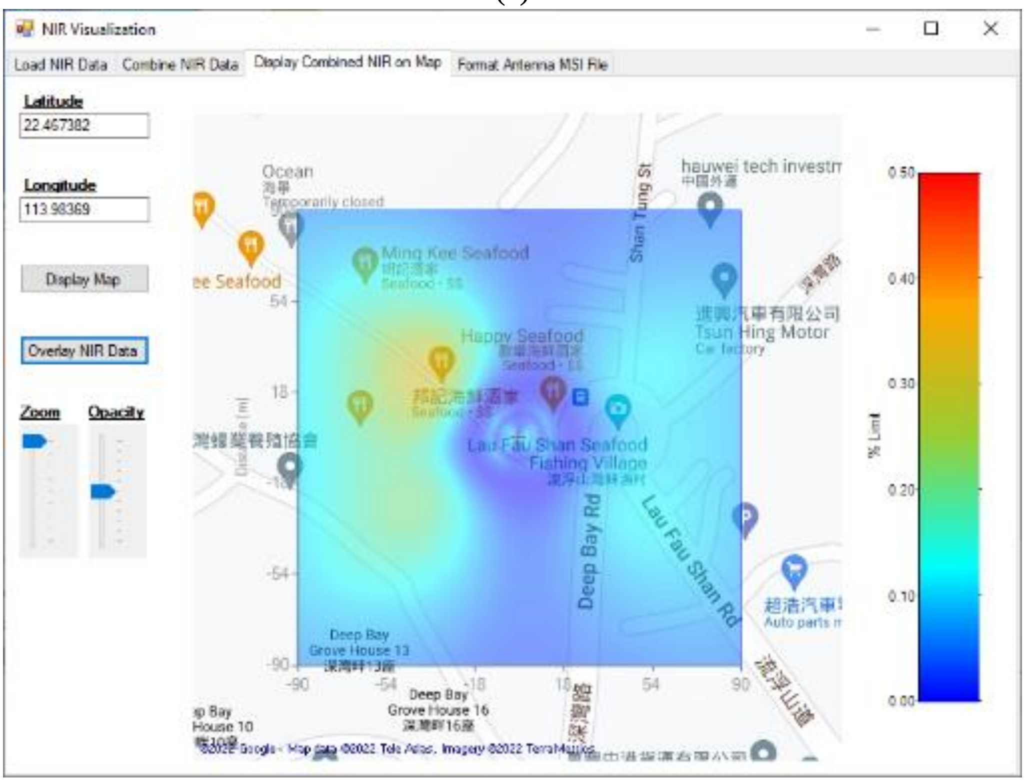
Theoretical Model

In Section 2.2, a theoretical model is presented for evaluating, in three-dimensional space, the incident power density from a single RBS operating in one particular frequency band (see equations (2-5) and (2-6)). When there is one or more RBS in the vicinity operating in a one or more frequency band, the theoretical model can be applied to evaluate the incident power density from *each* RBS operating in *each* frequency band, based on which the ICNIRP compliance level of the aggregated NIR level from all RBSs can be determined. In this study, computer simulations are used for applying the theoretical model; the NIR level from a single RBS can be evaluated using free[51] or commercially available software, and the aggregate NIR level from all RBSs being considered is determined using a proprietary software. For example, Figure G-1 shows the computer simulation results of the ICNIRP compliance level of the aggregated NIR level from four co-located RBSs applying the theoretical model, where Figure G-1a shows the individual NIR levels of each RBS and Figure G-1b shows the aggregate NIR level of all RBSs.

[51] The *EMF-estimator* software distributed as part of **[Ref 9]** is a free software that applies the theoretical model for evaluating the NIR levels RBSs.



(a)



(b)

Figure G-1: Computer simulation results of the ICNIRP compliance level of the aggregated NIR level from multiple RBSs. (a) Individual NIR levels of four co-located RBSs. (b) Aggregate NIR level of four co-located RBSs.

Simplified Model

Preliminary analysis of the NIR level at a location under consideration could be *extrapolated* from typical bounds obtained through approximations or field measurements. One approach to obtain an approximate bound on the NIR level for a single RBS operating in one particular frequency band is to assume the RBS antenna has omni-directional radiation pattern as illustrated in Figure G-2. It follows that the incident power density at an observation point *R* meters away from the RBS antenna can be approximated as (see equations (2-5) and (2-6))

$$S_{\text{inc}}(\theta, \phi, R, P_{\text{tx}}, T) = \frac{\text{EIRP}(\theta, \phi, P_{\text{tx}}, T)}{4\pi R^2} \approx \frac{\text{EIRP}}{4\pi R^2} \quad \text{(G-1)}$$

such that the NIR level *R* meters away from the RBS antenna is the same in all directions.

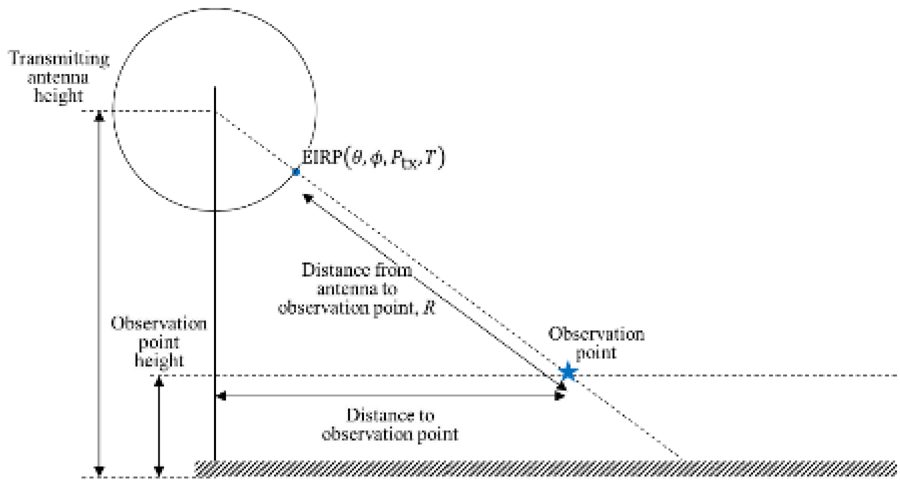


Figure G-2: Illustration of approximating NIR level at an observation point assuming RBS antenna has omni-directional radiation pattern.

Based on equation (G-1), the aggregate NIR level could be made by proportionally upscaling the bound on the NIR level by the total number of RBSs and the frequency bands that they operate on. In this study, a tool has been developed for implementing the simplified model and sample calculation results are shown in Figure G-3.

Distance from RBS Antenna, R (m)	Frequency Band (MHz)	Incident Power Density Reference Level (Wm^-2)	Total EIRP Of All RBSs Operating in This Frequency Band (W)	ICNIRP Compliance Level (%)
10	600	3	100	2.65
	700	3.5	100	2.27
	850	4.25	100	1.87
	900	4.5	100	1.77
	1800	9	100	0.88
	2100 to 43500	10	300	2.39
			Total ICNIRP Compliance Level (%)	11.84

Figure G-3: Sample results using the simplified model to predict NIR levels from a single or multiple RBSs operating in one or more frequency bands.

Annex H Field Measurement Methods and Results for Investigating the Technical Behaviors of RBSs That Make Use of mMIMO Antennas

In this study, field measurements were conducted in representative locations in Hong Kong for investigating the technical behaviors of RBSs that make use of mMIMO antennas.

Test Site 1

Test Site 1 is a site with RBSs at a rooftop at low height including one 4.9 GHz RBS that makes use of mMIMO antenna at Tsang Tai Uk Recreation Ground, Sha Kok Street, Sha Tin. Figure H-1 shows a photo of Test Site 1 and the directions of the boresight of the RBS antennas represented with arrows. The coverage area is divided into non-overlapping regions A, B, and C to carry out the following test cases and the measurement results are summarized in Table H-1. For all test cases, three sets of measurements were taken at 30 m from the RBS antennas, namely, 1) the broadband NIR level measured using a broadband power meter, 2) the worst case NIR level from the RBS estimated from reference signals measurements using a network scanner (see Annex E and Section 2.1.2.2), and 3) the actual NIR level from the RBS that makes use of an mMIMO antenna measured using a spectrum analyzer.

- Test Case 1: One to three terminals located in region A perform data download simultaneously. It is observed that the *total download data rate* of one to three terminals is constant and the NIR level from the RBS that makes use of an mMIMO antenna generally does not increase with increasing number of terminals performing data download simultaneously.

- Test Case 2: One terminal located in region A and one or more terminals in region B and region C perform data download simultaneously. It is observed that in region

A the NIR level from the RBS that makes use of an mMIMO antenna does not increase when terminals in non-overlapping regions B and C perform data download simultaneously.

- Test Case 3: One to three terminals located in region B perform data download simultaneously. It is observed that the *total download data rate* of one to three terminals is constant and the NIR level from the RBS that makes use of an mMIMO antenna generally does not increase with increasing number of terminals performing data download simultaneously.

- Test Case 4: One terminal located in region B and one or more terminals in region A and region C perform data download simultaneously. It is observed that in region B the NIR level from the RBS that makes use of an mMIMO antenna does not increase when terminals in non-overlapping regions A and C perform data download simultaneously.

- Test Case 5: One to two terminals located in region C perform data download simultaneously. It is observed that the *total download data rate* of one to two terminals is constant and the NIR level from the RBS that makes use of an mMIMO antenna generally does not increase with increasing number of terminals performing data download simultaneously.

- Test Case 6: One terminal located in region C and one or more terminals in region A and region B perform data download simultaneously. It is observed that in region C the NIR level from the RBS that makes use of an mMIMO antenna does not increase when terminals in non-overlapping regions A and B perform data download simultaneously.

Most importantly, it can be observed from Test Case 1 to Test Case 6 that the NIR level from the RBS that makes use of an mMIMO antenna is generally approximately 1/5 to 1/8 of the worst case NIR level from the RBS estimated from measured reference signal.

Figure H-1: Photo of Test Site 1 and the directions of the boresight of the RBS antennas represented with an arrow.

Table H-1: Test Site 1 NIR measurement results.

Test Case	Region of Measurements	Broadband Measurement	Frequency Band	Frequency-specific Measurement	Worst Case NIR Level from the RBS Estimated From Measured Reference Signal	mMIMO Reduction Factor
1	A	0.047 – 0.049 W/m^2	4.9 GHz	0.0017 – 0.0020 W/m^2	0.017 W/m^2	$\frac{1}{10}$ to $\frac{1}{8}$
			Below 3.6 GHz	0.0184 – 0.0209 W/m^2	0.028 W/m^2	N/A
2	A	0.045 – 0.049 W/m^2	4.9 GHz	0.0013 – 0.0020 W/m^2	0.017 W/m^2	$\frac{1}{13}$ to $\frac{1}{8}$
			Below 3.6 GHz	0.0183 – 0.0203 W/m^2	0.028 W/m^2	N/A
3	B	0.036 – 0.063 W/m^2	4.9 GHz	0.0019 – 0.0022 W/m^2	0.017 W/m^2	$\frac{1}{9}$ to $\frac{1}{8}$
			Below 3.6 GHz	0.0169 – 0.0312 W/m^2	0.036 W/m^2	N/A
4	B	0.056 – 0.069 W/m^2	4.9 GHz	0.0014 – 0.0015 W/m^2	0.017 W/m^2	$\frac{1}{12}$ to $\frac{1}{11}$
			Below 3.6 GHz	0.0270 – 0.0312 W/m^2	0.036 W/m^2	N/A
5	C	0.018 – 0.022 W/m^2	4.9 GHz	0.0005 – 0.0006 W/m^2	0.0028 W/m^2	$\frac{1}{6}$ to $\frac{1}{5}$
			Below 3.6 GHz	0.0109 – 0.0120 W/m^2	0.017 W/m^2	N/A
6	C	0.021 – 0.022 W/m^2	4.9 GHz	0.0005 – 0.0006 W/m^2	0.0028 W/m^2	$\frac{1}{6}$ to $\frac{1}{5}$
			Below 3.6 GHz	0.0118 – 0.0119 W/m^2	0.017 W/m^2	N/A

Test Site 2

Test Site 2 is a site with an indoor mmWave RBS that makes use of mMIMO antenna at the Hong Kong International Airport. Figure H-2 shows a photo of Test Site 2 and the direction of the boresight of the RBS antenna represented with an arrow. The coverage area is divided into non-overlapping regions A and B to carry out the following test cases and the measurement results are summarized in Table H-2. For all test cases, three sets of measurements were taken at 20 m from the RBS antenna, namely, 1) the broadband NIR level measured using a broadband power meter, 2) the worst case NIR level from the RBS estimated from reference signals measurements using a network scanner (see Annex E and Section 2.1.2.2), and 3) the actual NIR level from the RBS that makes use of an mMIMO antenna measured using a spectrum analyzer.

- Test Case 1: One to two terminals located in region A perform data download simultaneously. It is observed that the *total download data rate* of one to two terminals is constant and the NIR level from the RBS that makes use of an mMIMO antenna generally does not increase with increasing number of terminals performing data download simultaneously.

- Test Case 2: One terminal located in region A and one terminal located in region B perform data download simultaneously. It is observed that in region B the NIR level from the RBS that makes use of an mMIMO antenna does not increase when terminals in non-overlapping region B perform data download simultaneously.

Most importantly, it can be observed from Test Case 1 and Test Case 2 that the NIR level from the RBS that makes use of an mMIMO antenna is approximately 1/8 of the worst case NIR level from the RBS estimated from measured reference signal.

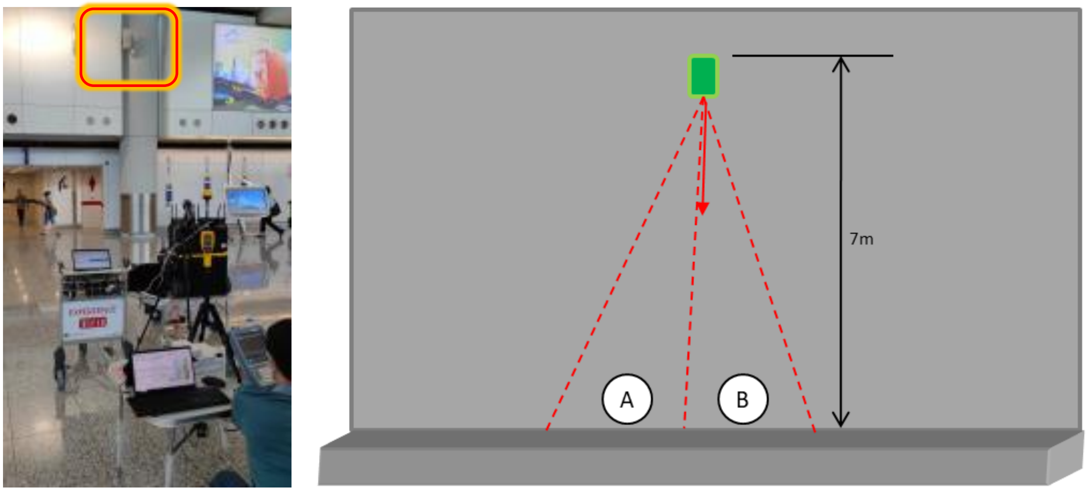


Figure H-2: Photo of Test Site 2 and the directions of the boresight of the RBS antennas represented with an arrow.

Table H-2: Test Site 2 NIR measurement results.

Test Case	Region of Measurements	Broadband Measurement	Frequency Band	Frequency-specific Measurement	Worst Case NIR Level from the RBS Estimated From Measured Reference Signal	mMIMO Reduction Factor
1	A	0.0052 – 0.0060 W/m^2	28 GHz	0.0027 – 0.0028 W/m^2	0.0234 W/m^2	$\frac{1}{9}$ to $\frac{1}{8}$
2	B	0.0060 W/m^2	28 GHz	0.0029 W/m^2	0.0234 W/m^2	$\frac{1}{8}$

Annex I Field Measurement Methods and Results for Evaluating the NIR Level When RBS Antennas Have Different Height Differences and Distances From Public-Accessible Areas

In this study, field measurements were conducted in representative locations in Hong Kong for evaluating the NIR levels in public-accessible areas. At a given measurement location, up to ten measurement points are selected on a case-by-case basis with the following considerations **[Ref 4]**.

- Position: Measurement points are selected from computer simulation results (e.g., positions expected to have relatively higher NIR levels) or along the directions of the main lobe or side lobes of the radiation patterns of the RBS antennas.
- Height above ground: Measurements should be made between 1.5m to 2.0m above ground at similar heights as the vital organs of the human body or on the same level as the RBS antenna if applicable.

At each measurement point, a broadband power meter is used to take Broadband Measurements to assess the aggregate NIR level. When applicable, a network scanner is used to take Frequency-specific Measurements to assess the NIR level on each frequency band used by the RBSs under investigation. The ICNIRP compliance level[52] of Broadband Measurements are evaluated assuming indoor and outdoor RBS emissions at 700 MHz or above, whereas the ICNIRP compliance levels of Frequency-specific Measurements are evaluated for each frequency band with respect to the relevant reference level (see equation (2-4)).

[52] At the time of this study, the 700 MHz band is the lowest frequency band assigned for the provision of public mobile services. The incident power density level corresponding to 700 MHz (see Table 2-3) is adopted for the calculation of the ICNIRP compliance level according to equation (2-4), i.e., the ICNIRP compliance level is given by $\left(\frac{\text{Total Incident Power Density}}{3.5\ \text{W/m}^2}\right)(100\%)$.

Test Site 3

Test Site 3 is a site with RBSs at a rooftop at low height in rural area at Lai Chi Kok Park Refreshment Kiosk. Figure I-1 shows a photo of Test Site 3 and a diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points. This site includes RBSs that make use of conventional non-mMIMO antennas as well as RBSs that make use of mMIMO antennas. At the time of this study, the emission levels of the RBSs that make use of conventional non-mMIMO antenna are 100 W ERP and the emission levels of the RBSs that make use of mMIMO antennas are 500 W ERP. The NIR measurement results when RBSs apply normal emission levels are shown in Table I-1 and it can be observed that the broadband NIR level is less than 5% of the ICNIRP compliance level across all measurement points. For the purpose of verifying that the ICNIRP safety limits can still be met when the emission levels of the RBSs are increased, a test was carried out by temporarily increasing the emission levels of the RBSs that make use of conventional non-mMIMO antenna to 500 W ERP. The NIR measurement results when RBS emission levels are increased are shown in Table I-2 and it can be observed that the broadband NIR level is less than 10% of the ICNIRP compliance level across all measurement points.

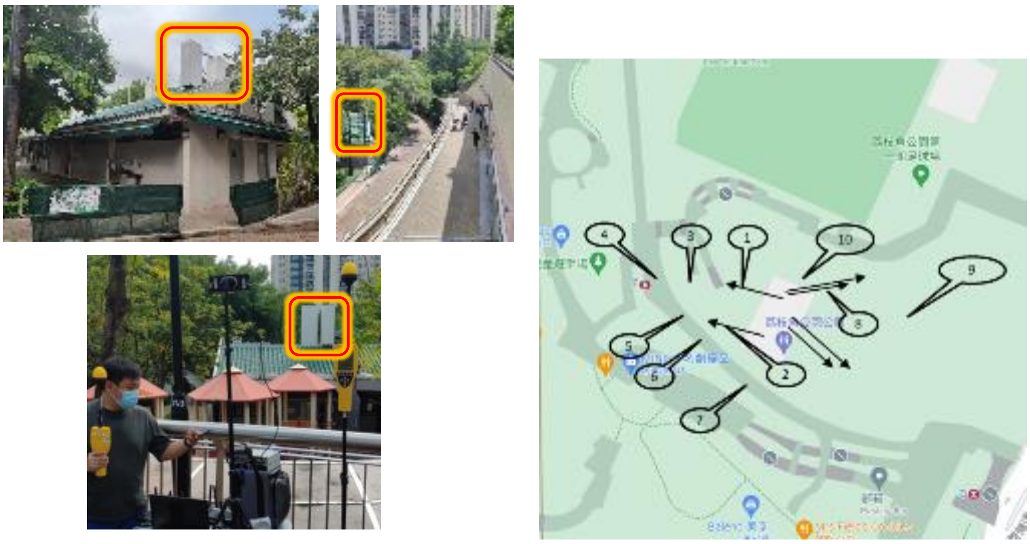


Figure I-1: Photo of Test Site 3 and diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points.

Table I-1: Test Site 3 NIR measurement results when RBSs apply normal emission levels.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m²)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m²)	ICNIRP Compliance Level (%)
1	0.0096	0.27	900 MHz	0.0015	0.03
			1800 MHz	0.0008	< 0.01
			2100 MHz	0.0008	< 0.01
			2300 MHz	0.0008	< 0.01
			2600 MHz	0.0004	< 0.01
			3500 MHz	0.0068	0.07
			Others	< 0.0001	< 0.01
2	0.0325	0.93	900 MHz	0.0059	0.13
			1800 MHz	0.0044	0.05
			2100 MHz	0.0053	0.05
			2300 MHz	0.0076	0.08
			2600 MHz	0.0018	0.02
			3500 MHz	0.0073	0.07
			Others	0.0002	< 0.01
3	0.0255	0.73	900 MHz	0.0012	0.03
			1800 MHz	0.0025	0.03
			2100 MHz	0.0021	0.02
			2300 MHz	0.0011	0.01
			2600 MHz	0.0003	< 0.01
			3500 MHz	0.0232	0.23
			Others	< 0.0001	< 0.01
4	0.0153	0.44	900 MHz	0.0011	0.02
			1800 MHz	0.0013	0.01
			2100 MHz	0.0006	< 0.01
			2300 MHz	0.0015	0.02
			2600 MHz	0.0005	< 0.01
			3500 MHz	0.0122	0.12
			Others	< 0.0001	< 0.01
5	0.0832	2.38	900 MHz	0.0222	0.49
			1800 MHz	0.0257	0.29
			2100 MHz	0.0145	0.14
			2300 MHz	0.0145	0.14
			2600 MHz	0.0062	0.06
			3500 MHz	0.0086	0.09
			Others	< 0.0001	< 0.01
6	0.0289	0.83	900 MHz	0.0177	0.39
			1800 MHz	0.0215	0.24
			2100 MHz	0.0213	0.21
			2300 MHz	0.0081	0.08
			2600 MHz	0.0006	< 0.01
			3500 MHz	0.0059	0.06
			Others	< 0.0001	< 0.01
7	0.0208	0.59	900 MHz	0.0046	0.10
			1800 MHz	0.0047	0.05
			2100 MHz	0.0017	0.02
			2300 MHz	0.0021	0.02
			2600 MHz	0.0009	< 0.01
			3500 MHz	0.0197	0.20
			Others	< 0.0001	< 0.01
8	0.0166	0.47	900 MHz	0.0010	0.02
			1800 MHz	0.0008	< 0.01
			2100 MHz	0.0008	< 0.01
			2300 MHz	0.0027	0.03
			2600 MHz	0.0002	< 0.01
			3500 MHz	0.0008	< 0.01
			Others	0.0103	0.29
9	0.0086	0.25	900 MHz	0.0008	0.02
			1800 MHz	0.0008	< 0.01
			2100 MHz	0.0000	< 0.01
			2300 MHz	0.0002	< 0.01
			2600 MHz	0.0000	< 0.01
			3500 MHz	0.0007	< 0.01
			Others	0.0061	0.17
10	0.0117	0.33	900 MHz	0.0017	0.04
			1800 MHz	0.0011	0.01
			2100 MHz	0.0015	0.02
			2300 MHz	0.0020	0.02
			2600 MHz	0.0001	< 0.01
			3500 MHz	0.0011	0.01
			Others	0.0042	0.12

Table I-2: Test Site 3 NIR measurement results when RBS emission levels are increased.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.0255	0.73	900 MHz	0.0064	0.14
			1800 MHz	0.0024	0.03
			2100 MHz	0.0027	0.03
			2300 MHz	0.0031	0.03
			2600 MHz	0.0015	0.01
			3500 MHz	0.0083	0.08
			Others	0.0011	0.03
2	0.0862	2.46	900 MHz	0.0214	0.47
			1800 MHz	0.0161	0.18
			2100 MHz	0.0187	0.19
			2300 MHz	0.0338	0.34
			2600 MHz	0.0063	0.06
			3500 MHz	0.0086	0.09
			Others	< 0.0001	< 0.01
3	0.0514	1.47	900 MHz	0.0108	0.24
			1800 MHz	0.0049	0.05
			2100 MHz	0.0032	0.03
			2300 MHz	0.0019	0.02
			2600 MHz	0.0004	< 0.01
			3500 MHz	0.0232	0.23
			Others	0.007	0.20
4	0.0289	0.83	900 MHz	0.0014	0.03
			1800 MHz	0.0013	0.01
			2100 MHz	0.0039	0.04
			2300 MHz	0.0034	0.03
			2600 MHz	0.0022	0.02
			3500 MHz	0.0122	0.12
			Others	0.0045	0.13
5	0.3327	9.51	900 MHz	0.0852	1.89
			1800 MHz	0.1216	1.35
			2100 MHz	0.1143	1.14
			2300 MHz	0.0341	0.34
			2600 MHz	0.0045	0.04
			3500 MHz	0.0087	0.09
			Others	< 0.0001	< 0.01
6	0.2924	8.36	900 MHz	0.0373	0.83
			1800 MHz	0.0949	1.05
			2100 MHz	0.0826	0.83
			2300 MHz	0.0236	0.24
			2600 MHz	0.0036	0.04
			3500 MHz	0.0064	0.06
			Others	0.0440	1.27
7	0.0717	2.05	900 MHz	0.0261	0.58
			1800 MHz	0.0130	0.14
			2100 MHz	0.0057	0.06
			2300 MHz	0.0020	0.02
			2600 MHz	0.0005	< 0.01
			3500 MHz	0.0161	0.16
			Others	0.0083	0.24
8	0.0446	1.27	900 MHz	0.0073	0.16
			1800 MHz	0.0021	0.02
			2100 MHz	0.0037	0.04
			2300 MHz	0.0079	0.08
			2600 MHz	0.0014	0.01
			3500 MHz	0.0006	< 0.01
			Others	0.0216	0.62
9	0.0179	0.51	900 MHz	0.0045	0.10
			1800 MHz	0.0037	0.04
			2100 MHz	0.0013	0.01
			2300 MHz	0.0018	0.02
			2600 MHz	0.0003	< 0.01
			3500 MHz	0.0011	0.01
			Others	0.0052	0.15
10	0.0193	0.55	900 MHz	0.0062	0.14
			1800 MHz	0.0029	0.03
			2100 MHz	0.0044	0.04
			2300 MHz	0.0073	0.07
			2600 MHz	0.0012	0.01
			3500 MHz	0.0009	< 0.01
			Others	< 0.0001	< 0.01

Test Site 4

Test Site 4 is a site with RBSs installed on a bus shelter on Kwun Tong Road, Kwun Tong. Figure I-2 shows a photo of Test Site 4 and a diagram illustrating the measurement points.

Figure I-2: Photo of Test Site 4 and the measurement points.

At the time of this study, the emission levels of the RBSs are 2.5 W ERP. The NIR measurement results when RBSs apply normal emission levels are shown in Table I-3 and it can be observed that the broadband NIR level is up to 15% of the ICNIRP compliance level directly below and very close to some of the RBS antennas (see Broadband Measurement results for measurement point 1 and 2 in Table I-3) and the broadband NIR level is below 5%

of the ICNIRP compliance level in all other positions around the bus shelter. Further investigation from Frequency-specific Measurements shows that when accounting for the effects of each frequency band the NIR level directly below and very close to some of the RBS antennas (see Frequency-specific Measurement results for measurement point 1 and 2 in Table I-3) is 10% of the ICNIRP compliance level, which is still well below the ICNIRP safety limits.

For the purpose of verifying that the ICNIRP safety limits can still be met when the emission levels of the RBSs are increased, two tests were carried out by temporarily increasing the emission levels of the RBSs to 10 W ERP and 25 W ERP. The NIR measurement results when RBS emission levels are increased are shown in Table I-4 and Table I-5. It can be observed from Table I-4 and Table I-5 that the NIR level is below the ICNIRP compliance level at all measurement points even when the RBS emission level is increased to 10 W ERP and 25 W ERP. In particular, Frequency-specific Measurements show that the NIR level directly below and very close to some of the RBS antennas (see Frequency-specific Measurement results for measurement point 1 and 2 in Table I-4 and Table I-5) is 10% and 20% of the ICNIRP compliance level when the RBS emission level is 10 W ERP and 25 W ERP, respectively.

Table I-3: Test Site 4 NIR measurement results when RBS emission level is 2.5 W ERP.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.4692	13.41	900 MHz	0.0081	0.18
			1800 MHz	0.0867	0.96
			2100 MHz	0.1848	1.85
			2600 MHz	0.0175	0.17
			3500 MHz	0.0053	0.05
			26/28 GHz	0.0006	< 0.01
			Others	0.1662	4.75
2	0.2600	7.43	900 MHz	0.0116	0.26
			1800 MHz	0.0635	0.71
			2100 MHz	0.1851	1.85
			2600 MHz	0.0045	0.05
			3500 MHz	0.0038	0.04
			26/28 GHz	0.0013	0.01
			Others	< 0.0001	< 0.01
3	0.0773	2.21	900 MHz	0.0074	0.17
			1800 MHz	0.0486	0.54
			2100 MHz	0.0396	0.40
			2600 MHz	0.0057	0.06
			3500 MHz	0.0025	0.03
			26/28 GHz	0.0001	< 0.01
			Others	< 0.0001	< 0.01
4	0.0955	2.73	900 MHz	0.0121	0.27
			1800 MHz	0.0805	0.89
			2100 MHz	0.0331	0.33
			2600 MHz	0.0029	0.03
			3500 MHz	0.0128	0.13
			26/28 GHz	0.0009	< 0.01
			Others	< 0.0001	< 0.01
5	0.0717	2.05	900 MHz	0.0104	0.23
			1800 MHz	0.0124	0.14
			2100 MHz	0.0697	0.70
			2600 MHz	0.0039	0.04
			3500 MHz	0.0141	0.14
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
6	0.1020	2.91	900 MHz	0.0100	0.22
			1800 MHz	0.0193	0.21
			2100 MHz	0.1261	1.26
			2600 MHz	0.0093	0.09
			3500 MHz	0.0223	0.22
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
7	0.0272	0.78	900 MHz	0.0090	0.20
			1800 MHz	0.0206	0.23
			2100 MHz	0.0187	0.19
			2600 MHz	0.0035	0.04
			3500 MHz	0.0080	0.08
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
8	0.0424	1.21	900 MHz	0.0041	0.09
			1800 MHz	0.0122	0.14
			2100 MHz	0.0284	0.28
			2600 MHz	0.0031	0.03
			3500 MHz	0.0049	0.05
			26/28 GHz	< 0.0001	< 0.01
			Others	<0.0001	< 0.01
9	0.0403	1.15	900 MHz	0.0062	0.14
			1800 MHz	0.0089	0.10
			2100 MHz	0.0588	0.59
			2600 MHz	0.0017	0.02
			3500 MHz	0.0032	0.03
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
10	0.0446	1.27	900 MHz	0.0069	0.15
			1800 MHz	0.0195	0.22
			2100 MHz	0.0090	0.09
			2600 MHz	0.0051	0.05
			3500 MHz	0.0066	0.07
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01

Table I-4: Test Site 4 NIR measurement results when RBS emission level is 10 W ERP.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.8883	25.38	900 MHz	0.0086	0.19
			1800 MHz	0.1915	2.13
			2100 MHz	0.6792	6.79
			2600 MHz	0.0165	0.17
			3500 MHz	0.0055	0.06
			26/28 GHz	0.0026	0.03
			Others	< 0.0001	< 0.01
2	0.3327	9.51	900 MHz	0.0109	0.24
			1800 MHz	0.0977	1.09
			2100 MHz	0.4123	4.12
			2600 MHz	0.0044	0.04
			3500 MHz	0.0041	0.04
			26/28 GHz	0.0053	0.05
			Others	< 0.0001	< 0.01
3	0.1155	3.30	900 MHz	0.0075	0.17
			1800 MHz	0.0717	0.80
			2100 MHz	0.1438	1.44
			2600 MHz	0.0058	0.06
			3500 MHz	0.0026	0.03
			26/28 GHz	0.0005	< 0.01
			Others	< 0.0001	< 0.01
4	0.2101	6.00	900 MHz	0.0122	0.27
			1800 MHz	0.1294	1.44
			2100 MHz	0.0715	0.71
			2600 MHz	0.0028	0.03
			3500 MHz	0.0130	0.13
			26/28 GHz	0.0039	0.04
			Others	< 0.0001	< 0.01
5	0.2054	5.87	900 MHz	0.0100	0.22
			1800 MHz	0.0138	0.15
			2100 MHz	0.1855	1.85
			2600 MHz	0.0040	0.04
			3500 MHz	0.0491	0.49
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
6	0.4346	12.42	900 MHz	0.0104	0.23
			1800 MHz	0.0220	0.24
			2100 MHz	0.4612	4.61
			2600 MHz	0.0090	0.09
			3500 MHz	0.0522	0.52
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
7	0.0561	1.60	900 MHz	0.0090	0.20
			1800 MHz	0.0285	0.32
			2100 MHz	0.0328	0.33
			2600 MHz	0.0043	0.04
			3500 MHz	0.0124	0.12
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
8	0.1453	4.15	900 MHz	0.0042	0.09
			1800 MHz	0.0170	0.19
			2100 MHz	0.0759	0.76
			2600 MHz	0.0034	0.03
			3500 MHz	0.0095	0.10
			26/28 GHz	< 0.0001	< 0.01
			Others	0.0353	1.01
9	0.0611	1.75	900 MHz	0.0058	0.13
			1800 MHz	0.0100	0.11
			2100 MHz	0.0938	0.94
			2600 MHz	0.0018	0.02
			3500 MHz	0.0036	0.04
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
10	0.0745	2.13	900 MHz	0.0072	0.16
			1800 MHz	0.0210	0.23
			2100 MHz	0.0172	0.17
			2600 MHz	0.0056	0.06
			3500 MHz	0.0066	0.07
			26/28 GHz	0.0006	< 0.01
			Others	0.0164	0.47

Table I-5: Test Site 4 NIR measurement results when RBS emission level is 25 W ERP.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.9475	27.07	900 MHz	0.0085	0.19
			1800 MHz	0.4038	4.49
			2100 MHz	1.4336	14.34
			2600 MHz	0.0177	0.18
			3500 MHz	0.0058	0.06
			26/28 GHz	0.0070	0.07
			Others	< 0.0001	< 0.01
2	1.4524	41.50	900 MHz	0.0120	0.27
			1800 MHz	0.2292	2.55
			2100 MHz	1.2580	12.58
			2600 MHz	0.0040	0.04
			3500 MHz	0.0042	0.04
			26/28 GHz	0.0134	0.13
			Others	< 0.0001	< 0.01
3	0.3210	9.17	900 MHz	0.0074	0.16
			1800 MHz	0.2513	2.79
			2100 MHz	0.2661	2.66
			2600 MHz	0.0057	0.06
			3500 MHz	0.0028	0.03
			26/28 GHz	0.0013	0.01
			Others	< 0.0001	< 0.01
4	0.3447	9.85	900 MHz	0.0120	0.27
			1800 MHz	0.3734	4.15
			2100 MHz	0.1715	1.71
			2600 MHz	0.0032	0.03
			3500 MHz	0.0133	0.13
			26/28 GHz	0.0099	0.10
			Others	< 0.0001	< 0.01
5	0.5889	16.83	900 MHz	0.0105	0.23
			1800 MHz	0.0176	0.20
			2100 MHz	0.4417	4.42
			2600 MHz	0.0041	0.04
			3500 MHz	0.1126	1.13
			26/28 GHz	< 0.0001	< 0.01
			Others	0.0024	0.07
6	1.3428	38.37	900 MHz	0.0102	0.23
			1800 MHz	0.0383	0.43
			2100 MHz	0.9467	9.47
			2600 MHz	0.0089	0.09
			3500 MHz	0.1751	1.75
			26/28 GHz	< 0.0001	< 0.01
			Others	0.1636	4.67
7	0.0490	1.40	900 MHz	0.0099	0.22
			1800 MHz	0.0414	0.46
			2100 MHz	0.0847	0.85
			2600 MHz	0.0039	0.04
			3500 MHz	0.0162	0.16
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
8	0.1872	5.35	900 MHz	0.0045	0.10
			1800 MHz	0.0217	0.24
			2100 MHz	0.2028	2.03
			2600 MHz	0.0031	0.03
			3500 MHz	0.0125	0.12
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
9	0.2054	5.87	900 MHz	0.0067	0.15
			1800 MHz	0.0213	0.24
			2100 MHz	0.2282	2.28
			2600 MHz	0.0014	0.01
			3500 MHz	0.0089	0.09
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
10	0.1086	3.10	900 MHz	0.0068	0.15
			1800 MHz	0.0535	0.59
			2100 MHz	0.0539	0.54
			2600 MHz	0.0055	0.06
			3500 MHz	0.0067	0.07
			26/28 GHz	0.0014	0.01
			Others	< 0.0001	< 0.01

Test Site 5

Test Site 5 is a site with RBSs at a podium facing a footbridge at 77 - 79 Granville Road, Tsim Sha Tsui. Figure I-3 shows a photo of Test Site 5 and a diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points. The emission levels of the RBSs are 100 W ERP. The NIR measurement results are shown in Table I-6, where it can be observed that at the footbridge the broadband NIR level is 0.97% of the ICNIRP compliance level. Even though some RBS antennas are facing the footbridge, the NIR level at the footbridge is low because the RBS antennas are sufficiently far away and tilted downwards.

Figure I-3: Photo of Test Site 5 and diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points.

Table I-6: Test Site 5 NIR measurement results.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m²)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m²)	ICNIRP Compliance Level (%)
1	0.0341	0.97	900 MHz	0.0030	0.07
			1800 MHz	0.0108	0.12
			2100 MHz	0.0063	0.06
			2600 MHz	0.0024	0.02
			3500 MHz	0.0240	0.24
			Others	< 0.0001	< 0.01

Test Site 6

Test Site 6 is a site with RBSs installed on a lamp pole on Victoria Road, Central and Western. Figure I-4 shows a photo of Test Site 6 and a diagram illustrating the direction of the boresight of the RBS antenna represented with an arrow and the measurement points. The emission levels of the RBSs are 100 W ERP. The NIR measurement results are shown in Table I-7, where it can be observed that the broadband NIR level is less than 5% of the ICNIRP compliance level across all measurement points.

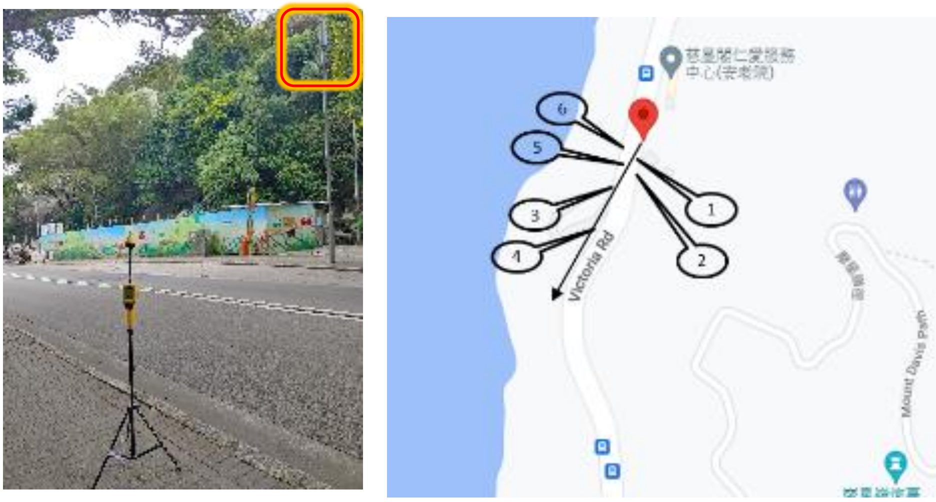


Figure I-4: Photo of Test Site 6 and a diagram illustrating the direction of the boresight of the RBS antenna represented with an arrow and the measurement points.

Table I-7: Test Site 6 NIR measurement results.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.0193	0.55	1800 MHz	0.0096	0.11
			2100 MHz	0.0114	0.11
			Others	< 0.0001	< 0.01
2	0.0239	0.68	1800 MHz	0.0251	0.28
			2100 MHz	0.0286	0.27
			Others	< 0.0001	< 0.01
3	0.0307	0.88	1800 MHz	0.0213	0.24
			2100 MHz	0.0167	0.16
			Others	< 0.0001	< 0.01
4	0.0032	0.09	1800 MHz	0.0009	0.01
			2100 MHz	0.0005	< 0.01
			Others	0.0018	0.05
5	0.0490	1.40	1800 MHz	0.0364	0.40
			2100 MHz	0.0091	0.09
			Others	0.0035	0.10
6	0.0383	1.09	1800 MHz	0.0236	0.26
			2100 MHz	0.0101	0.10
			Others	0.0046	0.13

Test Site 7

Test Site 7 is a site with rooftop level RBSs installed at external wall of a building at 612 - 618 Nathan Road, Mong Kok. Figure I-5 shows a photo of Test Site 7 and a diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points. The emission levels of the RBSs are 100 W ERP. The NIR measurement results are shown in Table I-8, where it can be observed that the broadband NIR level is less than 5% of the ICNIRP compliance level across all measurement points.

Figure I-5: Photo of Test Site 7 and diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points.

Table I-8: Test Site 7 NIR measurement results.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m²)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m²)	ICNIRP Compliance Level (%)
1	0.0490	1.40	900 MHz	0.0060	0.13
			1800 MHz	0.0128	0.14
			2100 MHz	0.0052	0.05
			2300 MHz	0.0045	0.04
			2600 MHz	0.0289	0.29
			3500 MHz	0.0052	0.05
			4900 MHz	0.0002	< 0.01
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
2	0.0514	1.47	900 MHz	0.0153	0.34
			1800 MHz	0.0166	0.18
			2100 MHz	0.0106	0.11
			2300 MHz	0.0038	0.04
			2600 MHz	0.0128	0.13
			3500 MHz	0.0045	0.04
			4900 MHz	0.0007	0.01
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
3	0.0468	1.34	900 MHz	0.0272	0.60
			1800 MHz	0.0166	0.18
			2100 MHz	0.0045	0.04
			2300 MHz	0.0106	0.11
			2600 MHz	0.0117	0.12
			3500 MHz	0.0052	0.05
			4900 MHz	0.0007	0.01
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01
4	0.1375	3.93	900 MHz	0.0446	0.99
			1800 MHz	0.0745	0.83
			2100 MHz	0.0239	0.24
			2300 MHz	0.0077	0.08
			2600 MHz	0.0383	0.38
			3500 MHz	0.0239	0.24
			4900 MHz	0.0002	< 0.01
			26/28 GHz	< 0.0001	< 0.01
			Others	< 0.0001	< 0.01

<u>Test Site 8</u>

Test Site 8 is a site with RBSs at a rooftop at low height in rural area at 2 - 4 Ching Tai Street, Lau Fau Shan, Yuen Long. Figure I-6 shows a photo of Test Site 8 and a diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points. The emission levels of the RBSs are 100 W ERP. The NIR measurement results are shown in Table I-9 and it can be observed the broadband NIR level is less than 5% of the ICNIRP compliance level across all measurement points.

Figure I-6: Photo of Test Site 8 and diagram illustrating the directions of the boresight of the RBS antennas represented with arrows and the measurement points.

Table I-9: Test Site 8 NIR measurement results.

Measurement Point	Broadband Measurement		Frequency-specific Measurement		
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)	Frequency Band	Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.0403	1.15	900 MHz	< 0.0001	< 0.01
			1800 MHz	0.0005	< 0.01
			2100 MHz	0.0005	< 0.01
			2600 MHz	0.0007	< 0.01
			3500 MHz	0.0001	< 0.01
			Others	0.0385	1.10
2	0.0344	0.98	900 MHz	< 0.0001	< 0.01
			1800 MHz	0.0066	0.07
			2100 MHz	0.0129	0.13
			2600 MHz	0.0007	< 0.01
			3500 MHz	0.0001	< 0.01
			Others	0.0141	0.40
3	0.0193	0.55	900 MHz	0.0002	< 0.01
			1800 MHz	0.0005	< 0.01
			2100 MHz	0.0011	0.01
			2600 MHz	0.0005	< 0.01
			3500 MHz	0.0008	< 0.01
			Others	0.0162	0.46
4	0.1227	3.50	900 MHz	0.0042	0.09
			1800 MHz	0.0032	0.04
			2100 MHz	0.0068	0.07
			2600 MHz	0.0045	0.04
			3500 MHz	0.0720	0.72
			Others	0.0320	0.91
5	0.0637	1.82	900 MHz	0.0029	0.06
			1800 MHz	0.0046	0.05
			2100 MHz	0.0480	0.48
			2600 MHz	0.0133	0.13
			3500 MHz	0.0767	0.77
			Others	< 0.0001	< 0.01
6	0.0032	0.09	900 MHz	< 0.0001	< 0.01
			1800 MHz	0.0005	< 0.01
			2100 MHz	0.0002	< 0.01
			2600 MHz	0.0002	< 0.01
			3500 MHz	0.0001	< 0.01
			Others	0.0022	0.06
7	0.0272	0.78	900 MHz	< 0.0001	< 0.01
			1800 MHz	0.0050	0.06
			2100 MHz	0.0128	0.13
			2600 MHz	0.0009	< 0.01
			3500 MHz	0.0227	0.23
			Others	< 0.0001	< 0.01
8	0.0223	0.64	900 MHz	< 0.0001	< 0.01
			1800 MHz	0.0008	< 0.01
			2100 MHz	0.0059	0.06
			2600 MHz	0.0079	0.08
			3500 MHz	0.0060	0.06
			Others	0.0017	0.05
9	0.0166	0.47	900 MHz	< 0.0001	< 0.01
			1800 MHz	0.0017	0.02
			2100 MHz	0.0061	0.06
			2600 MHz	0.0007	< 0.01
			3500 MHz	0.0011	0.01
			Others	0.0070	0.20
10	0.0239	0.68	900 MHz	0.0002	< 0.01
			1800 MHz	0.0019	0.02
			2100 MHz	0.0056	0.06
			2600 MHz	0.0010	0.01
			3500 MHz	0.0006	< 0.01
			Others	0.0146	0.42

Test Site 9

Test Site 9 is a site with indoor RBSs in shopping center at 2/F, Maritime Square2, Tsing Yi. Figure I-7 shows a photo of Test Site 9 and a diagram illustrating the measurement points. Measurements were taken at different heights at multiple measurement points directly underneath and between omni-directional antennas. The NIR measurement results are shown in Table I-10 and it can be observed the broadband NIR level is less than 1% of the ICNIRP compliance level across all measurement points[53].

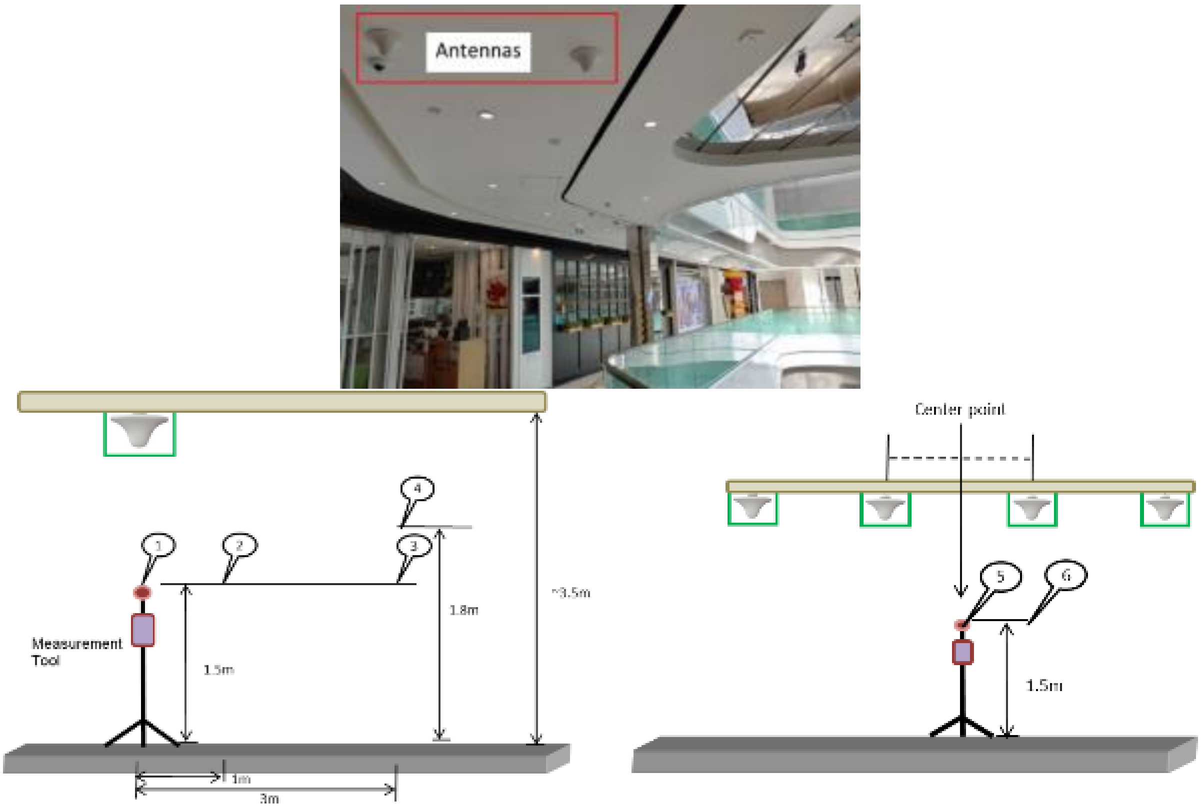


Figure I-7: Photo of Test Site 9 and the measurement points.

53 Indoor RBSs in shopping center often make use of distributed antenna system and each antenna could be shared by different combinations of low power RBSs operating in one or more frequency bands. Frequency-specific Measurements were not made because the broadband NIR level is very low even when measurements were made very near RBS antennas and frequency-specific NIR levels are insignificant.

Table I-10: Test Site 9 NIR measurement results.

Measurement Point	Broadband Measurement	
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.0325	0.93
2	0.0208	0.59
3	0.0128	0.37
4	0.0179	0.51
5	0.0027	0.08
6	0.0096	0.27

<u>Test Site 10</u>

Test Site 10 is a typical black spot with multiple RBS sites in the vicinity near the junction between Sai Yeung Choi Street South and Nelson Street at Mong Kok. Figure I-8 shows the RBS antenna locations and measurement points of Test Site 10 and the measurement results are summarized in Table I-11. It should be noted that the measurement points were selected by roaming around the area and using the broadband power meter to search for positions with the highest NIR levels. It can be observed that from Table I-11 that the broadband NIR level is less than 10% of the ICNIRP compliance level in this area.

Figure I-8: RBS antenna locations and measurement points of Test Site 10.

Table I-11: Test Site 10 NIR measurement results.

Measurement Point	Broadband Measurement	
	Total Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
1	0.30	8.57
2	0.13	3.71

Annex J Assessment Form for Routine Monitoring of NIR Levels From RBSs

Assessment Form for Routine Monitoring of NIR Levels From RBSs

1. Routine Monitoring Details

Date: ____________________________ Time: ____________________________

Address: ____

____

____

2. Broadband NIR Measurement Data

Measurement Equipment	
Manufacturer: _______________________	Model: ____________________________
Measurement Height: _________________	
Total Incident Power Density	**% of ICNIRP Compliance Level †**
____________________ W/m²	____________________ %

† As the 700 MHz band is the lowest frequency band assigned for the provision of public mobile services, the incident power density reference level corresponding to 700 MHz is adopted for the calculation of the ICNIRP compliance level, i.e., the ICNIRP compliance level is given by $\left(\frac{\text{Total Incident Power Density}}{3.5\ \text{W/m}^2}\right)(100\%)$.

Frequency-Specific Measurement Required: ☐ Yes ☐ No

3. Frequency-Specific Measurement Data (If Applicable)

Measurement Equipment	
Manufacturer: _______________________	Model: ____________________________
Measurement Height: _________________	
Total Incident Power Density	**% of ICNIRP Compliance Level**
____________________ W/m²	____________________ %

4. NIR Level of Each Frequency Band Allocated for the Provision of Mobile Services (If Applicable)

MNO‡	Lower Boundary of Frequency Band (MHz)	Upper Boundary of Frequency Band (MHz)	Incident Power Density (W/m^2)	ICNIRP Compliance Level (%)
3	870	877.5		
3	877.5	882.5		
4	930	940		
2	940	950		
1	950	955		
3	955	960		
3	1805	1815		
2	1815	1825		
2	1825	1835		
3	1835	1845		
1	1845	1855		
4	1855	1865		
1	1865	1875		
4	1875	1880		
3	2110.3	2115.3		
1	2115.3	2125.1		
2	2125.1	2139.9		
3	2140.1	2154.9		
4	2154.9	2169.7		
5	2300	2330		
1	2330	2360		
4	2360	2390		
6	2620	2640		
3	2640	2650		
2	2650	2670		
1	2670	2690		
4	3300	3330		
2	3330	3360		
3	3360	3380		
1	3380	3400		
1	3400	3460		
2	3460	3510		
3	3510	3560		
4	3560	3600		
1	4800	4840		
1	4840	4880		
2	4880	4920		
3	4920	4960		
Others	N/A			

‡ MNO 1 is China Mobile Hong Kong Company Limited. MNO 2 is Hong Kong Telecommunications (HKT) Ltd. MNO 3 is SmarTone Mobile Communications Ltd. MNO 4 is Hutchison Telephone Company Ltd. MNO 5 is 21Vianet Mobile Limited ("21Vianet Mobile"). MNO 6 is Genius Brand Limited ("GBL").

NIR Levels Are Within the ICNIRP Safety Limits: ☐ Yes ☐ No

Prepared By:

______________________________ ______________________________

(Signature & Name) (Date)

Approved By:

______________________________ ______________________________

(Signature & Name) (Date)