Spatial Analysis and Modeling of Non-Ionizing Radiations using a Two Ray Approach

Verónica A. García, Boris Ramos, Byron Floreano, Jorge Gómez

***Abstract*—** This paper uses a Two Ray approach for modeling the spatial diversity of Non-Ionizing Radiations measured at Prosperina campus of Escuela Superior Politécnica del Litoral (ESPOL), located in Guayaquil, Ecuador. Several measurements were made in the installed base stations of the two operators on campus, where we applied an improved version of the measurement procedure defined by the International Telecommunications Union (ITU). The ITU procedure was combined with the one recommended by CENELEC (Comité Européen de Normalisation Electrotechnique). The constructed model was able to simulate the multipath propagation of the transmitted signals, and generated similar values as the ones measured at three different heights at the same location, during the measurement campaigns around the cellular base stations of the two mobile operators on Campus. Finally as a complement, it was also investigated the simultaneous exposure to multiple sources in the closest point to the highest geographic location around Campus, the hill Cerro Azul, since it concentrates the greatest amount of radiating sources from different communication systems.

***Keywords*—** Non-Ionizing Radiations, Two Ray Model, Multiple Sources Effect.

I. Introduction

The ITU Recommendation for measuring Non-Ionizing Radiations (NIR) generated by frequency use of radio spectrum does not appropriately consider the spatial diversity of wireless propagation, since different values of power spectral density or electric field could be obtained from measurements made at different heights in the same geographic location [1]. On the other hand, the CENELEC procedure for NIR exposure measurements recommends taking the highest value of three measurements made at three different heights in the same location [2]. For this reason, we proposed an improvement to the ITU procedure by adding a new factor to the 12-points measurement assessed around the cellular base stations, which consists in measuring at three different heights in order to obtain a more precise evaluation of the electric field values in the vicinity of the antennas [3].

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After measuring the NIR at the base stations of the mobile operators on Campus, using our improved proposed scheme, we simulated these radiations using a simple ray-tracing method, which simplifies the modeling process of the multipath propagation of signals in a complex wireless channel. Specifically, we used a Two-Ray modeling approach, since we can assume that the received signal at the NIR measurement device arrives mainly from two paths: the direct Line of Sight (LOS) connection between the base station (BS) and the receiver, and the path arriving after reflection from the ground. In this case, the BS antenna is the radiating point where each path is modeled as an optical ray following the rules of geometric optics. Finally, we argue that this modeling approach is particular suitable for the type of environment we are dealing in this investigation.

The measurements obtained from simultaneous exposure to multiple radiating sources at the campus closest point to the hill Cerro Azul were also analyzed. The hill Cerro Azul concentrates the greatest amount of radiating sources in Guayaquil, including broadcasting, dispatching, and point to point services, among others. As a result of this analysis, it was assessed the aggregated contribution of different broadcasting and cellular electromagnetic radiating sources. The broadcasting services considered in this investigation include several FM radio and TV stations, and the cellular services analyzed in this study include only the base stations operating in the 850 MHz band.

The set of results obtained by the measurements and simulations performed in this investigation were compared with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) Levels of Reference, in order to verify their compliance with this international standard and to validate the modeling process presented in this research effort.

The rest of the paper is as follows. In Section 2 we present our proposed procedure for measuring NIR, which improves the ITU procedure by combining it with the one defined by CENELEC for NIR exposure measurements. In Section 3 we show the NIR measurement results and the corresponding analysis. In Section 4 we present the Two Ray modeling approach for NIR exposure. Section 5 shows the simulation results and the corresponding analysis. Finally, in Section 6 we present the Multiple Sources Effect of NIR and then we sum up some conclusions and present future work.

II. NIR MEASUREMENT PROCEDURE

The EN50400 Recommendation of CENELEC establishes a base station measurement procedure that considers the use of three heights at the measurement points around the cellular antennas, which are defined at 110cm, 150cm and 170cm above the floor. Once the measurements of the electric field at these three different heights are performed, the maximum is chosen as the final value [2]. This study proposes a new procedure that combines the measurement procedure defined by ITU with the one recommended by CENELEC. The ITU procedure considers twelve different geo-referenced measurement points located at the far field region, where each point is separated by thirty degrees with respect to its closest ones. The twelve measurement points are defined in the sites with public access closest to the base station. Therefore, the new proposed procedure that is used in our analysis considers the same twelve points around the base stations as defined by ITU, and the three different heights at each measurement point as defined by CENELEC [4, 5]

The spectrum analyzer used for the measurements campaign was the NARDA SRM-3000 and the exact locations of the measurement points corresponding to the two main cellular operators on campus, operator A and operator B, are shown in Figures 1 and 2. In these figures, it can be seen that there are no obstacles between the BS antennas and the measurement device.

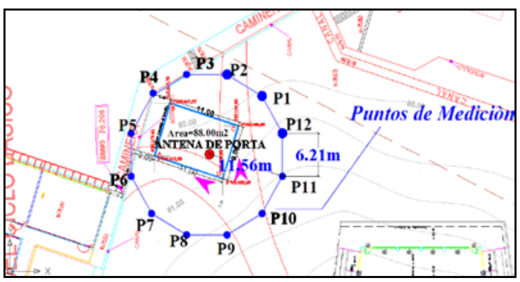

Fig. 1. Operator A base station

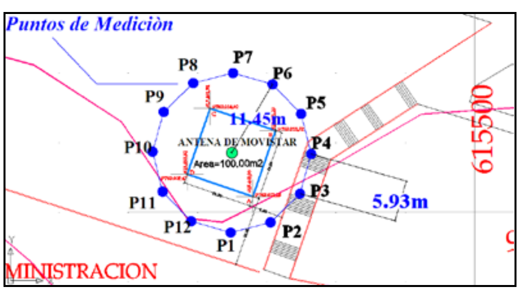

Fig. 2. Operator B base station

III. NIR MEASUREMENTS ANALYSIS

It is observed in Table I that the maximum values of electric field for both bands of frequencies (860MHz-880MHz and 890MHz-891.5MHz) used by the cellular operator A, not always happen at 1.5m, which is the height where measurements are realized in Ecuador, according to ITU's procedure. For instance, in the first band at Point 1 the maximum value occurs at 1.1m, while in Point 2 is at 1.7m; and for the second band at Point 1 the maximum value occurs at 1.1m while at Point 2 is at 1.5m.

In order to perform this analysis, it was established a percentage ratio between the measured electric field and the ICNIRP reference limits for public exposure to electric and magnetic fields. The reference limits of electric field intensity for both bands of frequencies for this cellular operator are defined as follows [5]:

1. 860MHz-880MHz: 40.79 V/m
2. 890MHz-891.5MHz: 41.05 V/m

As shown in Table I, the maximum ratio in the 860MHz-880MHz band is 5.1630%, and in the 890MHz-891.5MHz band is 1.3101%. These ratios correspond to measurements realized at 1.1m of height at Point 1.

TABLE I
RESULTS FOR 12 POINTS AROUND OPERATOR A ANTENNA

Height (m)	Points	Average Electric Field (mV/m)		Average Electric Field / Limit (%)	
		860-880 (MHz)	890-891.5 (MHz)	860-880 (MHz)	890-891.5 (MHz)
1.1		2106.00	537.80	5.1630%	1.3101%
1.5		1529.00	529.40	3.7485%	1.2896%
1.7	1	904.50	234.80	2.2175%	0.5720%
1.1		599.90	138.30	1.4707%	0.3369%
1.5		530.60	229.70	1.3008%	0.5596%
1.7	2	792.60	132.70	1.9431%	0.3233%
1.1		36.88	9.27	0.0904%	0.0226%
1.5		582.40	28.51	1.4278%	0.0695%
1.7	3	74.68	20.96	0.1831%	0.0511%
1.1		32.36	7.75	0.0793%	0.0189%
1.5		25.62	10.44	0.0628%	0.0254%
1.7	4	217.20	14.04	0.5325%	0.0342%
1.1		47.25	10.69	0.1158%	0.0260%
1.5		40.29	12.29	0.0988%	0.0299%
1.7	5	33.79	11.92	0.0828%	0.0290%
1.1		39.00	11.47	0.0956%	0.0279%
1.5		28.24	9.64	0.0692%	0.0235%
1.7	6	26.81	10.00	0.0657%	0.0244%
1.1		55.17	19.12	0.1353%	0.0466%
1.5		49.28	16.43	0.1208%	0.0400%
1.7	7	39.24	14.45	0.0962%	0.0352%
1.1		78.26	20.32	0.1919%	0.0495%
1.5		71.39	21.36	0.1750%	0.0520%
1.7	8	52.91	19.09	0.1297%	0.0465%
1.1		51.04	21.45	0.1251%	0.0523%
1.5		47.86	17.06	0.1173%	0.0416%
1.7	9	58.44	28.79	0.1433%	0.0701%
1.1		132.50	31.64	0.3248%	0.0771%
1.5		116.30	34.31	0.2851%	0.0836%
1.7	10	91.90	24.80	0.2253%	0.0604%
1.1		126.70	48.48	0.3106%	0.1181%
1.5		127.30	61.73	0.3121%	0.1504%
1.7	11	139.70	51.63	0.3425%	0.1258%
1.1		143.30	4.44	0.3513%	0.0108%
1.5		22.83	14.41	0.0560%	0.0351%
1.7	12	22.02	4.41	0.0540%	0.0107%

It is observed in Table II that the maximum values of electric field for both bands of frequencies (880MHz-890Mhz and 891.5MHz-894Mhz) used by cellular operator B not always happen at 1.5 m, which is similar to the operator's A case. It is important to note that the measurements were not made from Point 6 to Point 10, because these sites were not accessible by the measurement crew. The reference limits of electric field intensity for both bands of frequencies for this cellular operator are defined as follows [5]:

1. 880MHz-890MHz: 41.02 V/m
2. 891.5MHz-894MHz: 41.11 V/m

As also shown in Table II, the maximum ratio between the measured electric field and the corresponding ICNIRP limit in the 880MHz-890MHz band, is 1.9910%, and in the 891.5MHz-894MHz band is 0.1051%. These ratios correspond to measurements realized at 1.1 m of height at Point 11 and at 1.5 m of height at Point 3, respectively.

TABLE II
RESULTS FOR 12 POINTS AROUND OPERATOR B ANTENNA

Height (m)	Points	Average Electric Field (mV/m)		Average Electric Field / Limit (%)	
		880-890 (MHz)	891.5-894 (MHz)	880-890 (MHz)	891.5-894 (MHz)
1.1		594.30	7.5380	1.4488	0.0183%
1.5		651.00	4.9480	1.5870	0.0120%
1.7	1	374.80	4.4500	0.9137	0.0108%
1.1		35.76	4.4460	0.0872	0.0108%
1.5		30.12	4.0290	0.0734	0.0098%
1.7	2	36.02	4.3120	0.0878	0.0105%
1.1		36.85	4.4360	0.0898	0.0108%
1.5		21.13	43.2000	0.0515	0.1051%
1.7	3	4.42	35.4100	0.0108	0.0861%
1.1		30.18	4.8540	0.0736	0.0118%
1.5		25.73	4.4450	0.0627	0.0108%
1.7	4	28.67	4.4360	0.0699	0.0108%
1.1		93.97	7.5440	0.2291	0.0184%
1.5		84.75	6.3370	0.2066	0.0154%
1.7	5	41.00	5.0580	0.1000	0.0123%
1.1		816.70	4.3950	1.9910	0.0107%
1.5		42.20	4.4310	0.1029	0.0108%
1.7	11	51.92	4.4390	0.1266	0.0108%
1.1		143.30	4.4700	0.3493	0.0109%
1.5		22.83	4.4090	0.0557	0.0107%
1.7	12	22.02	4.4090	0.0537	0.0107%

The measurements at three different heights, as suggested by the CENELEC norm, proved to be an important consideration to take into account in any NIR measurement campaign [3]. In fact, it was observed in Point 11 of Table II that values of electric field around the cellular antennas, measured at 1.1 m of height, could be twenty times higher than the values obtained at 1.5 m of height, which is the height recommended by the ITU norm.

IV. NIR MODELING PROCEDURE

Several mathematical models have been used to assess NIR in the vicinity of electromagnetic radiating sources [6, 7]. On the other hand, several propagation models have been developed to characterize the propagation of the wireless channel for different telecommunication systems [8, 9, 10, 11, 12, 13, 14]. However, none of these models take into account the spatial diversity created by multipath propagation, which is characteristic of the type of environment found between the BS and the receiver, neither use a ray-tracing approach for modeling the received power.

The scenario analyzed in the modeling performed in this investigation is observed in Figure 3. In this figure, we can observe a BS, and a mobile station (MS) located at a distance X from the BS. The MS will represent our measurement device in this scenario. The height of the BS is h_b and the height of the MS is h_m. The distance X is equivalent to the sum of components X_1 and X_2, as indicated in the figure. The distance of the LOS path is equal to d, and the distance of the ground reflected path is equal to sum of components d_1 and d_2. In addition, we assume a total reflection ground, which implies that the incidence angle ϴ is equal than the reflection angle.

The general expression for a ray-tracing model of a fading channel simulates the received power as a function of the distance traveled by each path and the amplitude and phase of each received multipath component. Therefore, the received power will depend firstly on the received power P_0 measured at 1m from the BS, the reflection index of each path a_i, the total distance traveled by each path d_i, and the phase of each multipath component ϕ_i, which is represented in the following equation [15].

$$P_r = P_0 \left| \sum_{i=1}^{L} \frac{a_i}{d_i} e^{j\phi_i} \right|^2 \qquad (1)$$

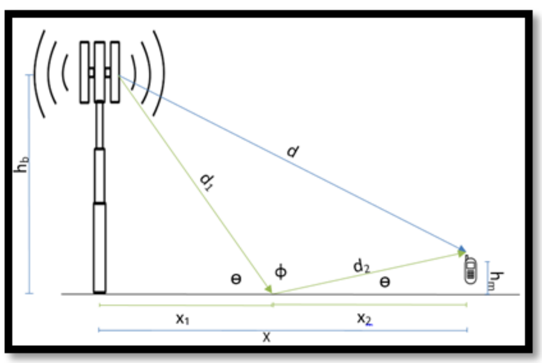

Figure 3. Basic Scenario for a Two Ray Model.

According to this, we can apply the general model described in Equation 1 to our Two Ray scenario described in Figure 3. The final expression after replacing the corresponding parameters of the LOS path (Path 1) and the ground reflected path (Path 2) in Equation 1 is shown in the following equation.

$$P_R = P_0\left(\frac{1}{d}e^{j\phi_1} + \frac{-1}{d_1+d_2}e^{j\phi_2}\right)^2 \quad (2)$$

The Effective Radiated Power (ERP) of the BS antenna is 67 dBm and h_b is 27 meters. The average distance X of the MS from the BS is 11,5 meters. Each simulated point will define its distance X by varying this randomly around its mean, following a Gaussian distribution with variance of 0.5 meters. A summary of the parameters of our Two Ray model is shown in Table III.

TABLE III
PARAMETERS VALUES

Parameters	Values
Bandwidth, BW	860-894 MHz
Base Station Height (hb)	27 m
Mobile Station Height (hm)	1-2 m
Distance between BS and MS (X)	11.5m
Effective Radiated Power	67 dBm

V. NIR MODELING RESULTS

The Figure 4 shows the variation of the Electric Field (E_{RX}) with respect to a referential value at 1 meter from the BS, for a frequency of 870 MHz and as a function of the MS height, h_m, and the distance X between the BS and MS. In this figure, it can be seen the E_{RX} high level of fluctuation, which can have deep fades in the order of tens of dB. For instance, values of E_{RX} simulated at the same distance X but for different values of h_m can have more than 20 dB of difference between each other.

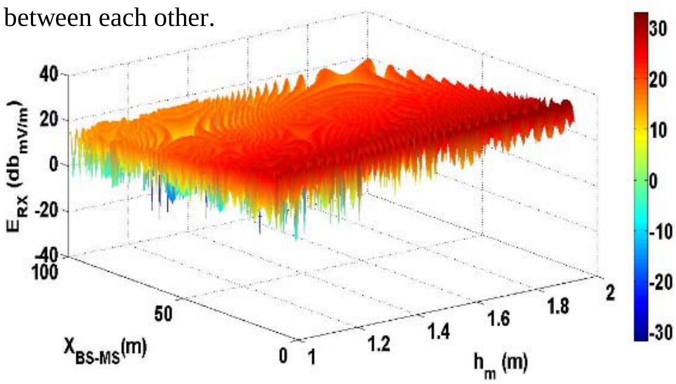

Fig 4: Simulated Received Electric Field at 870 MHz

The Figure 5 shows the E_{RX} simulated at the same distance X and for different values of h_m, considering the frequency band between 860 and 880 MHz. It can be seen the high level fluctuation of E_{RX}, as the value of h_m changes. On the other hand, the observed trend indicates the growth of the E_{RX} when the measurement height increases. However, it is observed a very deep fading as the measurement device performs very small movements and shifts

It can be observed in Tables IV and V the simulated values for each measured point around the BS of Operators A and B respectively. There is a strong correspondence between the measured values of NIR, which are shown in Tables I and II, and the simulated ones. There is also a clear similarity between the simulated and measured maximum ratios of exposure to NIR. The maximum simulated ratio of exposure to NIR for Operator A was 3.9828%, while the maximum measured ratio for the same operator was 5.163%. In addition, the maximum simulated ratio for Operator B was 4.1465%, while the maximum measured ratio for the same operator was 1.9910%.

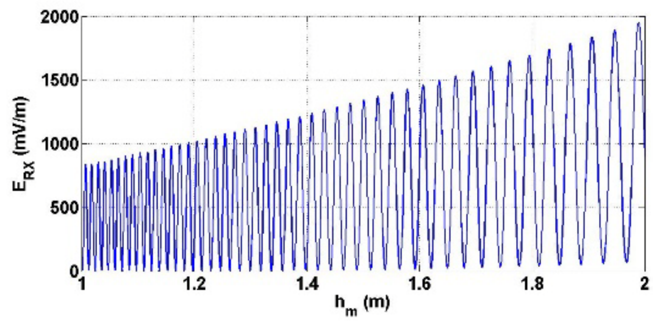

Fig 5: Electric Field vs hm (860-880 MHz Band)

TABLE IV
SIMULATED VALUES OPERATOR A

Height (m)	Points	Average Electric Field (mV/m)		Average Electric Field / Limit (%)	
		860-880 (MHz)	890-891.5 (MHz)	860-880 (MHz)	890-891.5 (MHz)
1.1		766.50	643.70	1.8672%	1.5781%
1.5		406.50	1044.10	0.9966%	2.5597%
1.7	1	807.00	685.20	1.9784%	1.6798%
1.1		918.90	1006.60	2.2528%	2.4678%
1.5		96.00	1379.30	0.2354%	3.3815%
1.7	2	66.80	1016.40	0.1638%	2.4918%
1.1		26.80	84.90	0.0657%	0.2081%
1.5		1188.40	11.90	2.9135%	0.0292%
1.7	3	1339.60	994.80	3.2841%	2.4388%
1.1		719.00	583.40	1.7627%	1.4303%
1.5		354.40	1101.80	0.8688%	2.7012%
1.7	4	745.00	185.30	1.8264%	0.4543%
1.1		409.10	77.40	1.0029%	1.9059%
1.5		594.20	950.80	1.4567%	2.3310%
1.7	5	1497.20	230.50	3.6705%	0.5651%
1.1		840.20	638.40	2.0598%	1.5651%
1.5		589.60	371.50	1.4455%	0.9108%
1.7	6	33.80	1495.80	0.0829%	3.6671%
1.1		865.00	965.50	2.1206%	2.3670%
1.5		145.90	1311.50	0.3577%	3.2152%
1.7	7	98.20	902.00	0.2407%	2.2113%
1.1		268.20	53.80	0.6585%	0.1319%
1.5		1189.50	14.30	2.9162%	0.0351%
1.7	8	348.70	1551.00	0.8549%	3.8024%
1.1		15.70	0.50	0.0385%	0.0012%
1.5		21.30	1362.20	0.0522%	3.3395%
1.7	9	62.40	1112.30	0.1530%	2.7269%
1.1		715.70	884.00	1.7546%	2.1672%
1.5		1267.30	143.40	3.1069%	0.3516%
1.7	10	1585.80	147.30	3.8877%	0.3611%
1.1		21.70	0.10	0.0532%	0.0002%
1.5		17.90	1375.50	0.0439%	3.3722%
1.7	11	69.50	1083.30	0.1704%	2.6558%
1.1		393.50	570.70	0.9647%	1.3991%
1.5		1385.80	20.90	3.3974%	0.0512%
1.7	12	1624.60	396.30	3.9828%	0.9716%

TABLE V
SIMULATED VALUES OPERATOR B

Height (m)	Points	Average Electric Field (mV/m) 880-890 (MHz)	Average Electric Field (mV/m) 891.5-894 (MHz)	Average Electric Field / Limit (%) 880-890 (MHz)	Average Electric Field / Limit (%) 891.5-894 (MHz)
1.1		395.40	1009.600	0.9639	2.4559%
1.5		1033.60	353.1000	2.5197	0.8589%
1.7	1	1700.90	50.8000	4.1465	0.1236%
1.1		23.50	424.1000	0.0573	1.0316%
1.5		1223.90	170.1000	2.9837	0.4138%
1.7	2	1252.00	518.4000	3.0522	1.2610%
1.1		0.10	634.6000	0.0002	1.5437%
1.5		1346.80	66.6000	3.2833	0.1620%
1.7	3	1043.10	737.7000	2.5429	1.7945%
1.1		0.20	613.7000	0.0005	1.4928%
1.5		1337.20	74.5000	3.2599	0.1812%
1.7	4	1065.20	714.6000	2.5968	1.7383%
1.1		900.40	68.3000	2.1950	0.1661%
1.5		175.70	1166.700	0.4283	2.8380%
1.7	5	115.80	1410.400	0.2823	3.4308%
1.1		0.60	750.4000	0.0015	1.8253%
1.5		56.90	1421.800	0.1387	3.4585%
1.7	11	40.40	1653.900	0.0985	4.0231%
1.1		952.10	133.6000	2.3211	0.3250%
1.5		256.50	1057.000	0.6253	2.5712%
1.7	12	73.90	1503.400	0.1802	3.6570%

The Tables VI and VII show the average simulated values for the two BS antennas corresponding to Operators A and B. It is observed that the average simulated values of NIR for the two mobile operators are well below the ICNIRP limit, which is a similar result as the one we obtained through the measurement campaigns as shown in Tables I and II. The maximum simulated ratio between the electric field and its corresponding limit was 3,58% as shown in Table VII.

TABLE VI
AVERAGE SIMULATED VALUES OPERATOR A

Height (m)	Average Electric Field (mV/m) 860-880 (MHz)	Average Electric Field (mV/m) 890-891.5 (MHz)	Average Electric Field / Limit (%) 860-880 (MHz)	Average Electric Field / Limit (%) 890-891.5 (MHz)
1.1	76.6	382.36	0.2351 %	2.3586%
1.5	116.15	58.33	0.0321 %	0.3176%
1.7	149.92	62.86	0.3486 %	0.3424%

TABLE VII
AVERAGE SIMULATED VALUES OPERATOR B

Height (m)	Average Electric Field (mV/m) 880-890 (MHz)	Average Electric Field (mV/m) 891.5-894 (MHz)	Average Electric Field / Limit (%) 880-890 (MHz)	Average Electric Field / Limit (%) 891.5-894 (MHz)
1.1	11.20	807.10	0.0273 %	1.9633%
1.5	500.70	880.00	1.2206 %	2.1406%
1.7	1470.10	82.70	3.5839 %	0.2012%

VI. MULTIPE SOURCES EFFECT OF NIR

The ITU-T K.52 Recommendation regarding simultaneous exposure to multiple sources verifies the compliance with the International Commission on Non-Ionizing Protection (ICNIRP) limits. This procedure combines the individual contributions of several communication systems operating at different frequencies. The measurement point for this analysis was defined as the site on the ESPOL campus closest to the hill Cerro Azul, which concentrates the highest number of radiating electromagnetic antennas in the City of Guayaquil, Ecuador. This point was located inside the soccer stadium of the university.

This ITU Recommendation establishes the compliance of the following expression in order to guarantee that the combined effect is below the recommended exposure limits [1]:

$$\sum_{i=100KHz}^{1MHz}\left(\frac{E_i}{c}\right)^2+\sum_{i>1MHz}^{300GHz}\left(\frac{E_i}{E_{l,i}}\right)^2\leq 1,$$

where:

Ei: is the electric field intensity at *i* frequency,
El, *i:* is the reference limit at *i* frequency,
c = 610/*f* V/m (f in MHz) for occupational exposure and 87/f1/2 V/m for public exposure in general.

The application of this expression using the results from the NIR measurements at the closest point to the hill Cerro Azul, inside the ESPOL campus, leads to the following relationship, which corresponds to the aggregated contribution of the FM, TV broadcasting, and 850 MHz cellular bands:

$$0.007513\leq 1,$$

This relation indicates that the overall exposure rate is more than one hundred times lower than the maximum aggregated exposition limit allowed by ICNIRP.

Finally, the NIR exposure generated by each type of communication system, which includes FM, TV broadcasting, and cellular systems, was analyzed individually for each system frequency band. The percentage ratio between the measured electric field and its corresponding ICNIRP reference limit was also calculated, with the following results:

FM:	0.0094%
TV BROADCASTING:	4.1228%
CELLULAR:	3.0985%

These results indicate that the TV broadcasting systems produce the highest level of Non Ionizing Radiation exposure at the closest point to the hill Cerro Azul, in the ESPOL campus. This result is contrary to the conventional belief that cellular systems are generating the highest level of NIR in urban settings. In fact, it was found in this university campus, that the NIR exposure of TV broadcasting systems is twenty five percent higher with respect to its corresponding ICNIRP limit, than cellular systems.

CONCLUSIONS

The ray-tracing approach for modeling base station NIR proved to be an effective method to estimate the electric field in the vicinity of a BS, since its implementation can be easily simplified by a Two Ray procedure. In fact, there was a strong correspondence between the simulated and measured values of NIR.

It was found a high level of fluctuation of the NIR measured and simulated values around a BS, which depends on the height of the measurement device, the distance between the BS and the measurement device, the frequency band, and the height of the BS antenna.

The CENELEC recommendation to measure at 1.1 m and 1.7 m of height besides the height of 1.5 m, as recommended by the ITU norm, proved to be an important consideration to take into account in any measurement campaign, since these two new measured values of Non Ionizing Radiation exposure could be twenty times larger than the value taken at 1.5 m of height.

It was observed that all the measured values of average electric field comply with ICNIRP reference limits, since the maximum ratio between the measured electric field and its corresponding limit was 5.1630%. In addition, the multiple source exposure in the ESPOL campus was more than one hundred times lower than the maximum aggregated exposition limit allowed by ICNIRP.

The TV broadcasting systems produce the highest level of Non Ionizing Radiation exposure in the university campus. It was found that the NIR exposure of TV broadcasting systems could be twenty five percent higher than the cellular system's case. This result is opposed to the conventional thinking that cellular systems produce the highest level of exposure to Non-Ionizing Radiations.

Future work should study the application of this approach to address other type of environments around the base station, such as the presence of buildings and vegetation.

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