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Measurement Methodology and Results of Measurements of the Man-made Noise Floor on HF in The Netherlands

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Abstract—Radio noise of man-made origin has been measured and studied since the fifties of the past century. From that time on, especially in the last two decades, the electromagnetic environment has changed due to the wide spread and increasingly complicated electronic and computing equipment in domestic and work premises. Not only the character of man-made noise has changed, but also the density of man-made noise sources increased. Users of radio receiving and communication equipment experience a limitation of functionality due to a risen noise floor and the appearance of a large numbers of interfering signals today. In order to quantify the observed increase a series of measurements of man-made noise levels in the well-spread MF, HF, and lower VHF bands of the Amateur Radio Service have been carried out in The Netherlands for a wide group of environments in all parts of the country. The data show that in City and in Residential environments the noise floor is significantly higher than would be expected from the current ITU-R noise floor data. The cumulative effect of the high density of sources is shown in the data. The measurement and analysis results could, with data from other investigations, be used in updating Recommendation ITU-R P.372-13.

Index Terms—Man-made Radio Noise, EMC, EMI.

I. Introduction

During the past decennia radio services experienced a serious increase in radio frequency interference levels due to man-made radio noise (MMN) as well as local electromagnetic interference (EMI) effects. These phenomena lead to a rise of the background noise floor, as has been shown in [1], [2], [3], [4], [5], [6]. During the standardization processes of network EMC standards, starting in 2000 in CEPT, later on continued in ETSI, CENELEC, and CISPR, the question of the existing levels of radio noise floor arose, together with how to measure those levels. In The Netherlands an expert group was formed in 2002 consisting of specialists from Agentschap Telecom (RA-NL), Royal Dutch Army, Royal Dutch Navy, Radio Netherlands World Service, ASTRON, Nedap (industry), and VERON (The Dutch radio amateur society, a member of the International Amateur Radio Union, IARU). The results were submitted to Study Group SG01 of ITU-R, what resulted in Report ITU-R SM.2055, Radio Noise measurements, [7]. This report was extended into Report ITU-R SM.2155, Man-made Noise measurements in the HF range, [8], and finally concluded in Recommendation ITU-R SM.1753-2, Methods for measurements of radio noise, [9]. A further study on noise measurement methods is found in [10].

From the early 50s on unintended generated man-made radio noise was investigated. The focus was on Very High Frequency (VHF) and Ultra High Frequency (UHF) frequencies mainly. Up to the late 70s the most important sources of man-made radio noise were automotive, power transport and power generating facilities. Other sources were industrial equipment, consumer electrical appliances and lighting systems [1], [2], [11-20]. From the white Gaussian noise (WGN) and the impulsive noise (IN) the latter was dominant by far, especially above 30 MHz, already documented in the Recommendation ITU-R P.372 [21]. Impulsive noise is caused by bursty emissions of short duration and usually with high peak values. Due to the low duty cycle the associated RMS power values are low. Due to their short burst time, the spectral occupation is broad. Mathematically, the ideal description is the Dirac Delta function. For the radio user it is relevant that the pulse rate is lower than the bandwidth of the receiver, while the pulse width is much smaller than the inverse of the receiver bandwidth. In that case the response of the receiver is the impulse response of its filters. This behaviour can be used to suppress impulsive noise.

In the 80s more electronic equipment arrived at consumer premises, progressively containing digital circuits. Also computers started to be used by consumers. In power supplies and adapters, the iron transformers were replaced by switching circuits, and appeared in the homes by large numbers. After the millennium-change internet, home networks, and faster computers changed the residential electro-magnetic environment even more. New systems arrived like Power Line Communication (PLC), xDSL networks, extended coaxial cable networks, solar panels with their convertors, battery chargers for electric bicycles etc., and last but not least light emitting diode (LED) lighting. For example reference [22] contains a well-documented case of interference from LED

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lighting apparatus to Band III DAB (digital audio broadcast) radios. All these new developments, although regulated by the EU EMC Directive [23] and EU Radio Equipment Directive [24], contribute to the current level of MMN.

Also the character of MMN has changed. The increasing source density and the dispersion in the propagation paths, converts IN into WGN as a result of the central limit theorem [25], [26], [27]. Besides that effect, newer MMN sources produce frequency-dependent EMI like harmonics of switching frequencies, and also broadband WGN. The accumulation of MMN from such sources results in higher levels of broadband WGN. These accumulation effects are also treated in reference [28], and in [29], chapter 8. In the composite MMN the share of WGN increased, while that of IN decreased as a result of European automotive EMC standards and of burying the powerlines [3], [4], [30]. These changes have a strong influence on the accumulation effect: While the high amplitude, low density, IN propagates over long distances [12], [16], [18], [31] and so determining the accumulated noise floor level in a large area, the lower amplitude, high density, WGN sets the level in a much smaller range of distances.

Current research on MMN is mainly directed towards radio noise inside industrial premises, the interference to short range devices [2], [32], and measurement methods [33]. In the literature the importance of MMN at frequencies below 30 MHz, generated by electronic equipment with a increasing number of switching devices, is addressed [34]. This importance is not only set by the level of unintended radiation per device, but also by the ever increasing number of devices. Other recent papers describe the study of indoor MMN in relation to digital broadcasting in the Medium Wave Band [35], [36], [37]. However, the measurement methods, as mentioned in these papers, use E-field antennas without sufficient counterpoise and/or grounding, resulting in large measurement uncertainties. The use of a magnetic loop antenna would be more adequate, also because of the use of ferrite antennas in the MW band receivers. Accumulation of skywave (reflected) MMN is also a threat to the radio users. In [29] a study about F-layer reflected noise from aggregated PLC systems is reported.

The recommendation ITU-R P.372-13 (2016) [21] contains the MMN levels based on measurements performed in the 1960s, while the electromagnetic environment has been changed drastically, as shown in the overview described before. The data about MMN in [21] has not been updated since 1974 [38], [39]. Therefore, updating the MMN levels given in [21] is of interest for planning new services and developing EMC (Electromagnetic Compatibility) standards**.**

In order to quantify the observed increase of the background noise floor by the radio users, and to explore the necessity of modifying noise floor data in [21], VERON carried out a measurement campaign to measure the MMN field strength levels and EMI under representative environments. For this purpose we made use of the hospitality of members of the VERON for reason of the availability of a large number of well-spread locations throughout The Netherlands in very divers environments. Although we performed the measurements on frequencies in the well spread frequency bands allocated to the Radio Amateur service, it is our intention to assess the harmful effects of increased MMN levels for all radio services.

The paper is organized as follows. First the measurements are described and the types of the noise sources are elucidated. In Section III the measurement setup is shown. In section IV the statistical analysis and evaluation is given, followed by the conclusion in section V.

II. DESCRIPTION OF THE MEASUREMENTS

In this paper we use the Euclidean reference frame. To denote a point in space we use the vector $\boldsymbol{x}=x\boldsymbol{i}_x+y\boldsymbol{i}_y+z\boldsymbol{i}_z$ in which x,y,z are scalars given in the SI-unit [m], $\boldsymbol{i}_x$, $\boldsymbol{i}_y$ and $\boldsymbol{i}_z$ are orthonormal unit vectors in the x, y and z direction respectively and bold face denotes a vector quantity. Time is denoted by the scalar t in [sec]. Time-harmonic signals are easily considered in the frequency domain by the well-known Fourier Transform. For the sake of simplicity the time factor will be omitted when working in the frequency domain. In case of a time-harmonic signal with period T the pertaining frequency is $f=1/T$ and given in Hertz [Hz].

A. The scope of the measurements

The methodology of the measurement campaign, described in this paper, differs from earlier MMN measurements. Instead of using measurement locations at large distances from buildings and homes, locations are sought representing the normal living conditions of radio spectrum users. Therefore 54 premises of VERON members were selected. These premises were well spread over rural areas, urban areas with a large variation in habitation densities, city environments, and also spread over the whole of the Netherlands: eleven of the twelve provinces were included. To complete the data set the measurement environment is extended with three locations representing a quiet rural environment and two locations to represent atypical environments. This extensive measurement campaign cover thus a representative geographic area of the main categories of the ITU. The measurements are carried out in the frequency range of 470 kHz up to 50.5 MHz. In this range IN is not an item of interest to the radio user, due to the general availability of noise blanker circuits. In modern Software Defined Radio (SDR) systems the noise blanker technique is also available, even in Analog to digital convertors, [40]. So the measurements in this paper are restricted to measuring WGN field strength levels, and will be compared to field strength levels, derived from noise power levels given in ITU-R P.372 [21]. The strict limitation to the frequency bands of the Amateur Radio Service has one draw-back: In these bands most Powerline Communication equipment (PLC) is notched.

Although in many places strong PLC signals were seen outside these bands, they do not fully contribute to the measured MMN levels, and we may expect higher MMN levels outside the notches, especially in the evening hours when PLC systems are mostly in full use.

B. Types of Noise Signals

For the purpose of the measurement campaign we differentiate between the following types of noise:

1 *Interfering signal, EMI*: an unwanted signal, usual man-made which is divided into two sub-classes:

1.1 *Narrowband EMI*: Bandwidth ⩽ 500 Hz, often an unmodulated carrier.

1.2 *Broadband EMI*: Bandwidth > 500 Hz, but smaller than the observed frequency band. Signal over the pertaining bandwidth may be partly Gaussian.

2 *Noise:* a stochastic signal or an accumulation of uncorrelated signals, not necessary Gaussian; Bandwidth much larger than the width of the observed frequency band. Within Noise three subclasses are identified:

2.1 Man-made noise originating from an individual specific local source.

2.2 Man-made noise originating from multiple local sources, generally cumulative.

2.3 Radio background noise, like atmospheric noise, galactic noise, and cumulative skywave MMN.

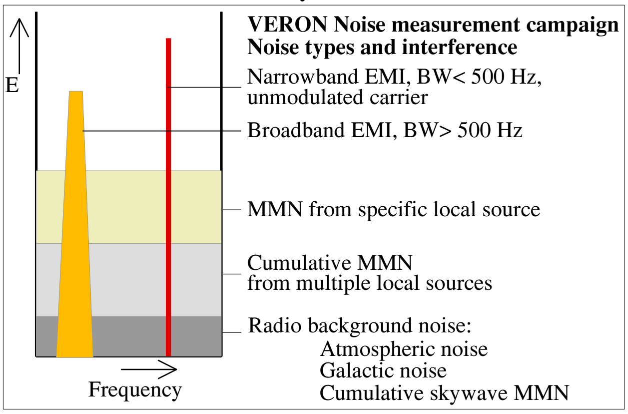

Fig. 1. Overview of types of noise signals considered in our research.

Man-made noise can be characterized by several parameters like the power spectral density, the amplitude probability distribution (APD), pulse spacing distributions (PSD), pulse duration distributions (PDD) [21], [39]. In this investigation we measure the power spectral density by using a bandwidth of 2700 Hz, representing the standard channel bandwidth for radio communication systems in the high frequency (HF) bands.

III. THE MEASUREMENT SETUP AND RESULTS

A. General description of the measurement campaign

Radio noise measurements have been performed at the premises of 54 radio amateurs, and at 5 other locations. Six categories of environment are defined:

1 *Quiet Rural area*: No residences, no infra structures within 1.5 km radius.

2 *Rural area*: up to 10 residences within a radius of 100 m, but at a distance of at least 100 m outside built-up area.

3 *Residential area-1*: 11 - 50 residences within 100 m.

4 *Residential area-2*: 51 - 100 residences within 100 m.

5 *Residential area-3*: >100 residences within 100 m.

6 *City area*: large apartment buildings, commercial & city centers. In this campaign we used the definition for *City area:*

   1 the residence is directly surrounded by shops and other city center activity, or

   2 the number of residences within a radius of 100 m is larger than 150, or

   3 the number of residences within a radius of 500 m is larger than 2000.

For every environment category a number of 10 locations measurements was targeted; practically the numbers were: Quiet Rural: 3, Rural: 10, Residential area 1: 12, Residential area 2: 14, Residential area 3: 10, and City: 8. Two locations were atypical and the measurement data were not used in this paper.

B. Measurement details

For the measurements a small receiver bandwidth of 500 Hz is used because of the difficulty to find frequency spaces free of radio signals, while the results are converted to the reference bandwidth of 2700 Hz. For this conversion we assume the noise to be Gaussian. Table I lists all the frequency bands wherein the measurements are performed. All measurements are carried out in periods with long daylight hours in the months from April until October, and in time slots wherein the level of atmospheric noise is minimal. At the MF and HF frequencies we assume that the dominant way of propagation of cumulating MMN is caused by the surface waves, inherently resulting in a vertical polarization. The measurement antennas are matched for this polarization. At the lower VHF band (6 m / 50 MHz) an antenna for horizontal polarization is used, assuming free space propagation. All measurement positions were in the open air, about 10 meters from outside wall of the premises, where applicable.

TABLE I
FREQUENCY RANGES AND TIME SLOTS USED IN THE MEASUREMENTS

Name of the frequency band	Frequency range of the measurements	Approximate timeslots of the measurements [h local time]
635 meter	470 - 480 kHz	12.00 - 14.00
160 meter	1.8 - 1.9 MHz	
80 meter	3.5 - 3.8 MHz	
60 meter	5.25 - 5.45 MHz	
40 meter	7.0 - 7.2 MHz	
30 meter	10.10 - 10.15 MHz	
20 meter	14.0 - 14.35 MHz	9.00 - 11.00
17 meter	18.068 - 18.168 MHz	
15 meter	21.0 - 21.45 MHz	
12 meter	24.89 - 24.99 MHz	
10 meter	28.0 - 29.7 MHz	
6 meter	50.0 - 50.5 MHz	14.00 - 15.00

C. Measurement equipment

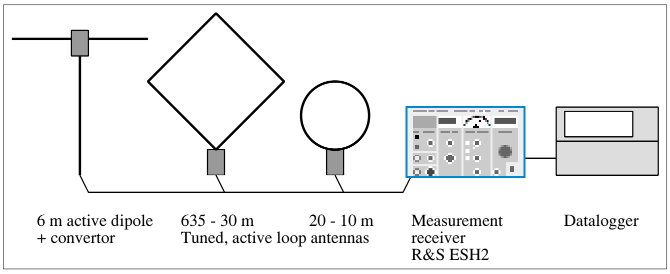

Fig. 2. The measurement equipment set-up.

The measurement equipment for the noise and EMI measurements are depicted in Fig. 2, and consists of a measurement receiver, three antennas, and a datalogger. The measurement receiver is a commercial Rohde & Schwarz ESH 2, self-calibrating. The datalogger digitizes the receiver output voltage, does all necessary processing and stores the results.

D. Reference noise field strength values

In [21] the MMN levels are given as linear regression curves, wherein the median values F_{am} of the antenna noise figure, F_a, depending on frequency f [MHz], is given by:

$$F_{am} = c - d \cdot \log f \quad (1)$$

The constants c and d are given by Table 2. According to equation:

$$E_n = F_a + 20 \cdot \log f_{\mathrm{MHz}} + 10 \cdot \log b_{\mathrm{Hz}} - 95.5 \text{ [dB}\mu\text{V/m]} \quad (2)$$

the noise field strength levels, E_n, can be calculated for a short monopole antenna above a perfect ground plane. These levels are plotted in Fig. 3.

TABLE II
CONSTANTS FOR CALCULATING MAN-MADE NOISE LEVELS

Environmental category	*c*	*d*	Frequency range [MHz]
City	76.8	27.7	0.3 - 250
Residential	72.5	27.7	0.3 - 250
Rural	67.2	27.7	0.3 - 250
Quiet rural	53.6	28.6	0.3 - 30
Galactic noise	52.0	23.0	10 - 150

E. Measurement results

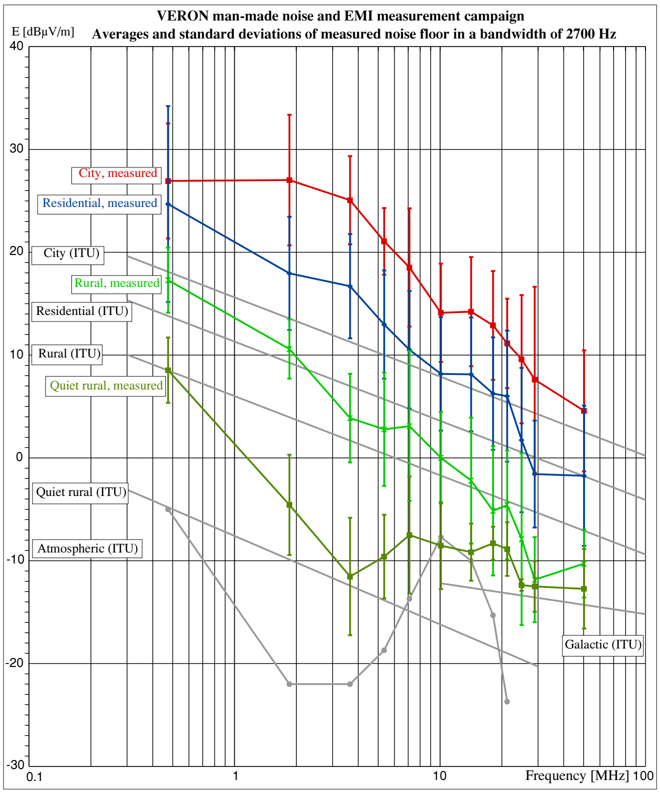

Fig. 3. Measurement results and reference curves.

The average values of the measured field strength levels for each frequency band were calculated, including the related standard deviation values. The measurement data for the four categories of environment are plotted in Fig. 3. The curves and main markers indicate the averaged noise field strength value pertaining to the associated environment. For completeness the standard deviations in the measurement results are plotted as well as the noise floor field strength levels as they are derived from [21]. It should be noted that Fig. 3 does not show the worse case measurement results. The worst case measured MMN levels exceed the Average levels by more than twice the shown values of the standard deviation.

IV. STATISTICAL ANALYSIS AND EVALUATION

Statistical tests are performed on the measurement data using the Student t-test as described in [41]. A two-tail test is chosen, using a level of significance, $\alpha = 0.05$, which means a Type I error risk of 5 %, a common used value. The population is the total number of enrolled amateur radio station in The Netherlands per type of environment, including the measurement locations in Quiet Rural environments. The population means, μ, are given by the noise field strength levels as given in Fig. 3. The sample in the statistical meaning is the set of noise floor field strength measurements within a type of environment. The null hypothesis, H_0, is formed by the assumption that noise levels have not changed since the time and method of measurement of the data in [21]. The alternative hypothesis, H_1, assumes a change of the noise floor. So the rejection of H_0 means a statistical relevant increase of the noise floor, or a statistical relevant decrease of the noise floor. The number of samples, n, differs for the individual environments: $n = 3$ for Quiet Rural, $n = 10$ for Rural, $n = 36$ for Residential, and $n = 8$ for City. Table III shows the results of the statistical analysis, and is denoted as follows. The red cell color indicates that for that frequency band a statistically significant increase in the noise floor has been found. The blue cell color means that a statistically significant decrease has been observed. For the sake of completeness the average values and standard deviations of our measurements are given per frequency band.

Table III
RESULTS OF THE STATISTICAL ANALYSIS OF THE INCREASE OF THE RADIO NOISE FLOOR

VERON man-made noise measurement campaign						Statistical analysis of increase of noise floor							
Band	n	635m	160m	80m	60m	40m	30m	20m	17m	15m	12m	10m	6m	
City	8	+ 8.8 ±5.6	+13.4 ±6.4	+13.8 ±4.3	+11.1 ±3.2	+9.4 ±5.8	+6.2 ±4.8	+7.5 ±5.3	+7.0 ±5.3	+5.7 ±4.4	+4.7 ±6.2	+3.2 ±9.0	+2.1 ±5.9	AV SD
Resi- dential	36	+10.9 ±9.5	+8.7 ±5.5	+9.7 ±5.1	+7.3 ±5.3	+5.7 ±5.7	+4.3 ±5.5	+5.7 ±5.5	+4.7 ±5.5	+4.9 ±6.4	+1.1 ±7.0	-1.7 ±5.2	0.1 ±6.8	AV SD
Rural	10	+8.8 ±3.2	+6.6 ±2.9	+2.2 ±4.3	+2.4 ±5.5	+3.6 ±7.3	+1.7 ±4.4	+0.7 ±6.1	-1.4 ±6.3	-0.4 ±8.4	-3.2 ±8.4	-6.6 ±4.1	-3.2 ±3.3	AV SD
Quiet rural	3	+13.3 ±3.2	+5.3 ±4.9	+0.9 ±5.7	+4.3 ±4.1	+6.2 ±5.7	-0.8 ±4.2	+0.8 ±2.8	+4.7 ±1.6	+4.3 ±2.6	+1.0 ±0.6	+1.1 ±2.5	+1.6 ±3.9	AV SD
Statistical relevance:				Increase			Neutral			Decrease		AV: [dBμV/m] SD: [dB]		

From the results, shown in Fig. 3 and Table III, several things can be learned:

- Although the measurement results for the quiet rural environment shows a statistical significant rise in the noise floor at the lowest frequency band, its not clear that this is caused by MMN only. From the expected levels of MMN Quiet Rural and of Atmospheric Noise, as shown in Fig. 3 where they coincide at 470 kHz and cross between 7 and 19 MHz, one may conclude that Atmospheric noise may contribute to the measurement results too.
- For the rural environment the rise in MMN is statistically significant on the two lowest frequency bands. On the other side of the spectrum we see a relative decrease of MMN on the 10 and 6 meter bands. Reduced ground wave propagation, caused by low conductivity of the ground (the measurements were performed during the summer half year), may explain this reduction.

- In residential environments the increase of the noise floor level by MMN is very clear, and is statistically significant for all frequencies, except the highest three bands.
- In city environments the rise of the MMN level, relative to ITU-R P.372-13, is complete, and is statistically significant for all frequencies, except the highest three bands.

A. Regression lines

In a second step of the statistical analysis the correlation between the mean values of measured field strength levels and the frequency bands is determined per type of environment, and so calculating the regression lines. Fig. 4 shows the change of the slopes and of the mean levels of the regression lines from the basic Recommendation CCIR 372-4 (1986) [42] / Report 258-4 (1982) [38], which is just copied in the later ITU-R P.372 versions, into the measured values. The slope and the Man-Made Noise field strength level at a frequency of 1 MHz are shown in Table IV.

TABLE IV
SLOPE AND LEVEL OF REGRESSION CURVES ACCORDING THE MEASUREMENTS

Environment type:	Slope [dB/log (MHz)]	$E_{N@1\,MHz}$ [dBμV/m]	Correlation coefficient r
City	-12.58	28.00	-0.9459
Residential	-13.61	22.06	-0.9752
Rural	-14.64	13.53	-0.9808

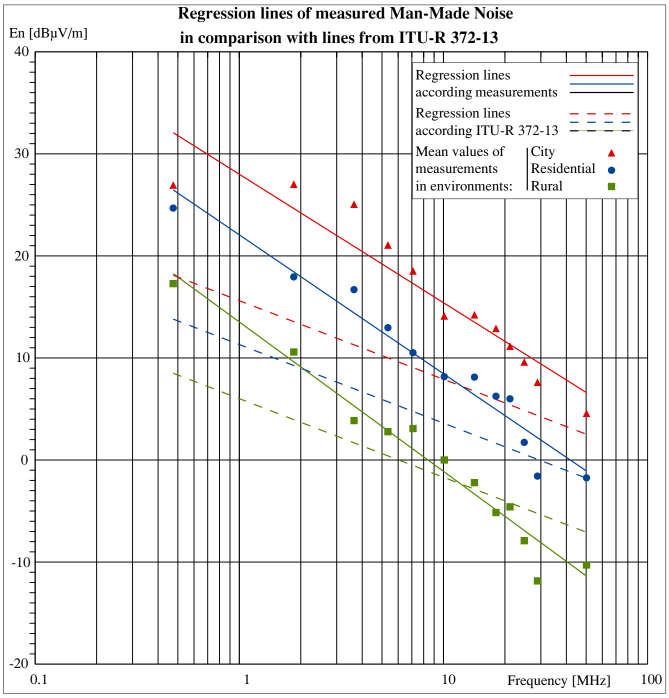

Fig. 4. Regression lines of measured Man-Made Noise in comparison with the regression lines in ITU-372-13.

Also shown are the Pearson correlation coefficients r, which show a high level of correlation. The slope and field strength levels in Table IV can be calculated back to Noise Figures as used in ITU-R 372-13. Inverse use of formula (2) results in new values for the constants c and d. The frequency range is limited to 50 MHz, because there is no measuring data available for higher frequencies. Based on our measurements we anticipate a modification of ITU-R 372. In Table V our proposition for possible modifications is presented.

TABLE V
PROPOSED CONSTANTS FOR FUTURE VERSION OF ITU-R 372

Environmental category	c	d	Frequency range [MHz]
City	89.2	32.6	0.3 - 50
Residential	83.3	33.6	0.3 - 50
Rural	74.7	34.6	0.3 - 50

V. CONCLUSION

The measurements at 54 different locations show that man-made activities generate an increase of the Man Made noise floor in the Netherlands. In general there is a statistically significant increase of the MMN floor in comparison with the reference levels as given in Recommendation ITU-R P.372-13 [21]. This increase is highest in dense build-up regions like city centre, where increases up to 14 dB averaged, with peak values over 20 dB, exist. In residential environments the increase is also very significant, although gradual lower with lower habitation densities.
As the measurements were performed in various locations, from lakes and woods at far distances from the built-up area to residential areas in various densities of habitation and in city centers, it is our opinion that we have gained a representative picture of noise floor levels in the Netherlands. After many years of EMC-regulation in the European Union and the assumption that the MMN-environment in the Netherlands does not differ from other developed (EU) countries, we have no reason to believe that performing our measurements in other countries under similar circumstances would lead to different results. In order to verify that other countries have similar MMN-environments, we encourage other groups to conduct measurements too. Consequently, we conclude from our measurements that the data about Man-Made Noise in Recommendation ITU-R P.372-13 needs updating, and we made a suggestion for new values for the relevant parameters.
As known from previous work [28,29] our measurements and analysis have confirmed the accumulation effect caused by the increasing density of interfering sources in close proximity. From this observation we can conclude that the paradigm of Man-Made Noise has shifted over time: In conventional EMC-standards it is assumed that only one single (sub)system is present in the close vicinity of a radio receiver, but clearly, this is not the case any more.
Finally it is noted that due to the constant change in our modern day society similar noise-floor measurements should be conducted frequently to keep track on the evolution of the MMN floor.

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