Analysis of the radiated electric field strength from in-house G.fast2 data carrying wire-line telecommunication network

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Abstract
G.fast profile 212a technology is the perfect choice for an operator offering a broadband service, as it operates using the existing copper telecommunications infrastructure (cables) already installed in user premises. Unfortunately, such telecommunications infrastructure is not designed to transmit data at high frequencies used by G.fast technology, resulting in radiation during signal transmission. This radiation can have a direct impact on the performance and reliability of radio services operating in the same frequency range. In order to limit such radio interference, International Telecommunication Union proposed radiation limits for wired telecommunications networks. This paper provides a comparison between ITU-T K.60 Recommendation with the measurements of the electric field radiation from the telecommunications network when the G.fast profile 212a signal is transmitted through different types of telecommunications cables. The aim of this comparison is to assess whether the radiation from the telecommunications network in this study meets the radiation limits defined in ITU-T K.60 Recommendation and, therefore, whether this radiation can be a source of interference to radio services operating in the same frequency range. In addition, this paper provides an analysis of the impact of cable construction on the total irradiated field from the in-house part of the telecommunications network.

1 | INTRODUCTION

User demands for higher data rates are constantly increasing, forcing telecommunications operators to invest in the development of telecommunications infrastructure. Although fibre to the home architecture (FTTH) is emerging as the best long-term solution for providing gigabit connectivity, difficulties in the installation process, legal constraints, and the cost of fibre deploying postpone the massive use of fibre. In order to provide ultra-fast broadband access to places where the use of FTTH is not a cost-effective solution, it is necessary for telecommunications operators to effectively exploit and reuse the existing copper telecommunications infrastructure [1, 2]. A technology that is attracting increasing interest from operators looking to provide fibre-like throughput over existing copper telecommunications network is G.fast profile 212a (G.fast2) technology. This technology uses a frequency bandwidth up to 212 MHz offering an aggregated data rate of up to 2 Gbps in local loops shorter than 200 m [3–5]. Moving the fibres closer to user’s premises and reusing the existing copper telecommunications infrastructure enables ultra-fast data transmission without “last-mile” installation challenges, which enables the implementation of G.fast2 technology in an economically and technically feasible way [6, 7].

Although G.fast2 uses an improved precoding scheme, ultra-fast data rate is generally achieved by using higher frequency bandwidth compared to the bandwidth used by other DSL technologies (e.g., ADSL and VDSL technologies). Unfortunately, increasing throughput by increasing frequency bandwidth has a number of disadvantages. It is known that a copper wire is not a perfect transmission medium and that part of the signal energy is radiated in the air when the signal passes through the wire [8–10]. The radiated electromagnetic field from the telecommunications network is a potential source of interference to radio services operating in the same frequency range disabling the radio service from operating as planned [11]. This is especially important in critical services where such radiation can directly affect the safety and security of human
life. In order to limit unwanted emissions from the telecommunications network, various radiation limits have been proposed. The most commonly used radiation limits for the assessment of radio interference caused by the radiation from wireline telecommunications networks is defined in ITU-T K.60 Recommendation.

Although customer premise equipment (CPE) has been identified as a main source of interference in the in-house part of the telecommunications network, cables used for data transmission can also negatively contribute to the entire interference situation [12]. This paper presents the results of measuring the electric field ($E$-field) radiation from the in-house part of the telecommunications network during the transmission of the G.fast2 signal, as well as a comparison of measured values and the ITU-T K.60 radiation limit values. The measurements were performed when using different types of telecommunications cables for data transmission to assess the effect of cable construction on the entire radiated field from the in-house part of the telecommunications network.

The paper is organized as follows: Section 2 provides information on the network topology as well as technical specifications regarding the tested cables. Section 3 provides ITU-T K.60 Recommendation that define radiation limits. Section 4 provides information on the measurement methodology and procedure, while the measurement results, along with the $E$-field radiation rating, are presented in Section 5. Concluding remarks are given in Section 6.

**2 | BROADBAND TELECOMMUNICATION INFRASTRUCTURE**

Increased demand for ultra-fast broadband brings fibre deeper into the distribution network. While fibre is still considered the most future-proof access technology for high broadband services, for most internet providers, the use of fibre can be both; expensive and time consuming. The introduction of fibre is particularly problematic in the final meters of the telecommunications network leading to and within user’s premises (“last-mile” part of the network). This is the main reason why internet operators, in order to provide ultra-fast broadband connection in an economically acceptable way, are forced to combine existing copper telecommunications infrastructure with optical fibres [13–16].

Depending on the spot where the fibre terminates, telecommunications topologies vary. The telecommunications topology mainly used for G.fast2 signal transmission is fibre to the distribution point topology (FTTdp), fibre to the building topology (FTTB) and fibre to the door topology (FTTD) [17, 18]. FTTdp network topology leads fibre cables to a distribution point (dp) located at a distance of up to 200 m from the user’s premise which is then connected to the existing copper infrastructure that connects each individual user [19]. In the FTTB topology, the fibre reaches the boundary of the building (e.g. basement) while in FTTD scenario, the fibre reaches the boundary of the living space, such as the connection point outside the user’s premise wall. FTTx topology mainly used for G.fast2 technology is shown in Figure 1.

According to [8], the wire-line telecommunications network includes telecommunications cables, their in-house cable extensions and telecommunications terminal equipment that are crucial to ensure efficient operation between internet service provider (ISP) and CPE. The critical part of the telecommunications network, in terms of interference, is the in-house part of the network. Interference problems within in-house part of the telecommunications network are often results of the radiation from the CPE and radiation from telecommunication cables used for data transmission. In order to ensure that electrical equipment does not interfere with other services and equipment, CPE equipment must be designed in accordance with the relevant electromagnetic compatibility (EMC) requirements [20, 21]. The EMC principle of telecommunications cables is that the radiation from communication signals should be kept inside the cables. Since most telecommunications cables already installed in the user’s premises are not designed for data transmission at frequencies used by the G.fast2 technology, radiation from the cables occurs. This radiation can increase overall network radiation above the defined radiation limits and is usually result of insufficient shielding requirements, inadequate cable construction, improper cable installation and/or inadequate cable maintenance.

The most common technique used to reduce cable radiation is twisting the wires in the cable (twisted cables). A twisted cable consists of two insulated wires twisted around each other with a twist length of less than $\lambda_{\text{min}}/4$, where $\lambda_{\text{min}}$ represents the
minimum wavelength of the signal in the cable. The reduction in radiation in a pair of twisted wires results from the fact that the two wires carry signals of equal magnitude and opposite sign, resulting in mutual cancellation of the field generated by the cable (Figure 2(b)). If the imperfection of the geometrical symmetry of the wire pair with respect to the earth is present, differential signal will generate a common-mode excitation of the wire pair, resulting with increased cable radiation (Figure 2(c)) [22, 23].

To describe the ability of a cable to reduce unwanted radiation, the term balanced is used. Cable balance, in terms of voltage, is defined as [24]

$$b_v = \frac{U_{\text{com}}}{U_{\text{diff}}}$$

(1)

where $U_{\text{com}}$ represents the common mode voltage and $U_{\text{diff}}$ the differential mode voltage. On the decibel scale, cable balance is often described as longitudinal conversion loss (LCL), defined as [25]

$$LCL = -20 \cdot \log_{10} (b_v) \text{ [dB]}$$

(2)

To additionally reduce radiation of copper cables as well as to reduce external radio impact, the twisted copper wires in modern xDSL cables are covered with aluminium tape (shielded cables). Although unshielded cables have purer technical characteristics than shielded cables, unshielded cables are often used as part of the wire-line telecommunications network due to lower costs. Taking this into account and the fact that in-house installation is usually made of unshielded cables, interference in the reception of radio signals operating in the same frequency band as G.fast2 technology could be expected. In order to analyse the level of radiation from the in-house part of the telecommunications network when different types of cables are used, in this study radiation was observed when a cable TK33U, a cable TK59U, an UTP cat.5E cable and an S/FTP cat.7A cable are used. The cables were selected to reflect the main design features and specifications of the telecommunications cables mainly used for xDSL signal distribution. The technical specifications of cables used in this paper are given in Table 1. The mark of the cable core construction consists of three groups of number symbols mutually connected by "×" sign, marking: first group—number of basic elements in the cable; second group—way of stranding of basic elements; third group—cable conductor diameter.

### Table 1: Construction data of cables

| Construction | Wire insulation/sheath insulation | Shielded         |
|--------------|----------------------------------|------------------|
| TK33U        | 3×4×0.4 solid polyethylene/polyethylene | No               |
| TK59U        | 3×4×0.4 Fomed+solid polyethylene/polyethylene | Yes (aluminium tape) |
| UTP cat.5E   | 4×2×0.4 polyethylene/polyvinyl chloride | No               |
| S/FTP cat.7A | 4×2×0.4 polyethylene/polyvinyl chloride | Yes (aluminium foil+copper braid) |

3 | SPECTRAL COMPATIBILITY AND RADIATION LIMITS FOR WIRE-LINE TELECOMMUNICATION NETWORKS

In recent decades, the use of radio frequency spectrum has increased dramatically. The RF spectrum enables significant advances in technology from the mobile network to high-speed wireless Internet. Without its application our modern life would not be possible. Since the radio frequency spectrum is a limited natural resource, it must be managed in a professional, objective and efficient manner. Achieving efficient radio spectrum management implies interference-free operation of radio communication services.

Unfortunately, data transmission over a wired telecommunications network causes electromagnetic radiation and potentially interferes with a radio service operating nearby [26]. To achieve ultrafast throughput, modern broadband wire-line technologies use higher frequency bandwidth [27]. However, higher frequencies also mean higher signal attenuation (shorter loop length), higher power consumption and increased number of radio services that could be affected by cable radiation. Radio services which could be affected by the network radiation when transmitting G.fast2 signal are: amateur services, aeronautical services, broadcasting services, government services, radio navigation services, maritime services, distress and safety services, etc. The radiated electromagnetic field can cause intolerable error in signal reception or, if the radiation is too high, it can cause loss of communication. This scenario has to be avoided on priority basis, especially if the radiation affects services that have a direct impact on human life, such as: security services, safety services and the welfare of social services.

Telecommunications authorities have proposed various radiation restrictions to prevent unwanted emission from the...
telecommunications network as well as to protect radio services operating in the same frequency range as broadband wire-line services. The most commonly used recommendation defining radiation restrictions from wire-line telecommunications networks is ITU-T K.60 Recommendation proposed by the International Telecommunication Union (ITU). Although the ITU-T K.60 Recommendation sets radiation limits for the frequency range from 9 kHz to 3 GHz, in this paper and due to the specification of the nominal frequency range of the antenna, only limits from 30 to 212 MHz are considered. This frequency range also corresponds to the frequency range used by G.fast2 technology when compatibility with VDSL2 profile 30a technology must be achieved. According to the ITU-T K.60 Recommendation, the radiation limit for the previously defined frequency range is 40 dB μV/m at a distance of 3 m from the wire-line telecommunications network [8].

4 | MEASUREMENT SETUP

G.fast2 technology enables Gigabit connection by transmitting high frequency signals over an existing copper telecommunications network. To assess the radiation level from the in-house part of the telecommunications network, the E-field radiation level is measured when G.fast2 modem and telecommunication cable are installed in the anechoic RF chamber while the digital subscriber line access multiplexer (DSLAM) is installed outside the chamber. All electronic equipment used in this paper complies with EMC directive and standards (Council Directive 2015/863/EU and 2014/30/EU), that is, the emitted emissions from electrical devices are below the defined radiation limits. Although the electronic equipment used in this study was manufactured in accordance with EMC directive, it does not mean that overall radiation from telecommunications network in user premises meets the radiation limits defined by the international authorities. The reason for this is that the telecommunications network in addition to electronic equipment also consists of existing copper telecommunications cables that are not usually designed to transmit data at frequencies used by G.fast2 technology, resulting in increased radiation when the signal passes through it [28]. Therefore, in order to analyse the influence of cable construction on the measured level of E-field radiation, the measurement is performed for different types of telecommunication cables. The individual cable length is 6 m, and the technical specifications of the cables used in this study are given in Section 2.

Anechoic chamber is an ideal location to test radiation from a telecommunications network since it is a radiation free environment where only radiation from an object of interest (G.fast2 modem and copper telecommunication cable in this case) is present. To reduce reflection inside the chamber, pyramidal RF absorbers were placed on the walls inside the chamber. The internal dimensions of the anechoic chamber in which the measurements were performed were 7.62 × 5.18 × 5.49 m (length × width × height).

The measurements of the radiated E-field level were performed using an R&S ESMD receiver and a Schwarzbeck VULB 9160 linear polarized logarithmic broadband antenna designed for a nominal frequency range from 30 to 1000 MHz. The antenna was placed on a tripod 1.7 m above the ground level and 3 m from telecommunications cable, as defined in [8]. The measurement setup is shown in Figure 3.

The R&S ESMD receiver was set to measure the frequency range from 30 to 212 MHz with a frequency step of 51.75 kHz. The frequency step was equal to the subcarrier spacing in G.fast2 technology as defined in [29]. To achieve the E-field level in dB μV/m, the antenna correction factor as well as the connection loss and cable loss between the antenna and the receiver were added to the values measured on the receiver.

5 | MEASUREMENT RESULTS

The radiated E-field level from telecommunications network installed in the anechoic chamber is measured when the antenna is placed in a vertical position because a higher radiated signal is measured in that position. According to the specifications defined in [8], the E-field radiation was measured using a peak detector and a measuring bandwidth of 120 kHz. The G.fast2 aggregate transmit power is set up to 4 dBm as it is specified in [29]. Due to the comparison simplicity, the mean value, $\bar{E}$, of the radiated E-field value was calculated for each cable used in this paper. To obtain the $E$-field reference level, the measurement was first performed when the G.fast2 modems were turned off. This measurement result represents the noise level in the anechoic chamber and will be used for comparative reasons to estimate the radiation level from telecommunications network installed in the chamber. The result of the referent (noise) level measurement is presented in Figure 4.

Since the radiation from the modem power supply unit (AC/DC adapter) also contributes to the total network radiation, in order to estimate this radiation, the measurement was performed when one modem was turned on as well as when six modems were turned on (in this measurement mode, the modems were not synchronized with the DSLAM; there was no data transmission in the telecommunications cable). The result of this measurement is shown in Figure 5. As expected, radiation in the anechoic chamber increases with increasing number of modems in power-ON mode.

The results of measuring the $E$-field radiation when the G.fast2 signal is transmitted through a TK33U cable are shown in Figure 6. To analyse the cumulative effect of network radiation increasing when several twisted wire pairs in the cable are used simultaneously, $E$-field radiation is measured when one twisted pair of wires (one modem) is used, as well as when six twisted pairs of wires (six modems) are used for data transmission. Although a situation where several twisted wire pairs are simultaneously used in a single user premise to transfer G.fast2 data is unlikely to be found in practice, this measurement can be used as a good indicator to estimate the increase in radiation when the number of used wire pairs increases. Figure 6 shows that, although the CPE equipment used in this study meets all relevant EMC requirements, radiation from the in-house part of the telecommunications network is significantly above the
radiation limits when G.fast2 signal is transmitted through a TK33U cable, for example the highest $E$-field level is measured at 128.6 MHz and is 48.5 dB $\mu$V/m which is 8.5 dB above limit defined in ITU-T K.60 Recommendation. Such high radiation increase is result of the common mode current produced by the G.fast2 modem which then propagates to the modem G.fast port and radiates to the surrounding area via the connected cable. In addition, Table 2 shows that mean $E$-field level in the frequency range from 30 to 212 MHz when G.fast2 signal is not transmitted is $\bar{x} = 6.4$ dB $\mu$V/m and when G.fast2 signal is transmitted via a single twisted wire pair of TK33U cable mean $E$-field level increases to $\bar{x} = 33$ dB $\mu$V/m. The radiation additionally increases when the number of used twisted wire pairs increases, for example when six twisted wire pairs are used $\bar{x} = 43.1$ dB $\mu$V/m which is 36.7 dB above the referent
TABLE 2 Measurement results

|                | Mean value, $\bar{x}$ [dB $\mu$V/m] | Subcarriers above ITU limit [%] | Max. value [dB $\mu$V/m]/freq. [MHz] |
|----------------|--------------------------------------|---------------------------------|---------------------------------------|
| Noise          | 6.4                                  | 0                               | 12/151.9                              |
| TK33U (1 twisted_pair) | 33                                   | 16.8                            | 48.5/128.6                            |
| TK33U (6 twisted_pair)  | 43.1                                 | 76.3                            | 59.4/121.2                            |
| TK95U (1 twisted_pair)  | 26.3                                 | 0.6                             | 43.5/164.8                            |
| TK95U (6 twisted_pair)  | 36.8                                 | 25.7                            | 51/164.1                              |
| UTP cat.5E (1 twisted_pair) | 27.7                                 | 0.2                             | 41.6/119.45                           |
| UTP cat.5E (4 twisted_pair) | 34.5                                 | 12.6                            | 47.2/106.9                            |
| S/FTP cat.7A (1 twisted_pair) | 25.4                                 | 0                               | 39/122.8                              |
| S/FTP cat.7A (4 twisted_pair) | 33.7                                 | 6.6                             | 45.5/82.7                             |
| TK33 unbalanced (1 twisted_pair) | 46                                   | 79.5                            | 59.8/75                               |

FIGURE 8 Measured E-field radiation from UTP cat.5E telecommunication cable

$E$-field level and 10.1 dB above the mean $E$-field level when one pair of twisted wires is used. Since the R&S ESMD receiver is set up to measure the frequency range from 30 to 212 MHz with a frequency step of 51.75 kHz (which is equal to the subcarrier spacing), it can easily be shown that 16.8% of the subcarriers used for data transmission have $E$-field level above the limits defined in the ITU-T K.60 Recommendation when one twisted wire pair of TK33U cable is used.

From the presented results it is evident that the proposed radiation limits are too optimistic regarding the radiation from telecommunications network of which the TK33U cable is an integral part. The presented results also indicate the need to significantly reduce the G.fast power spectral density in order to achieve compatibility with the proposed radiation limits if a TK33U cable is used.

The measurement results of the $E$-field radiation when the G.fast signal is transmitted through the TK95U telecommunication cable is shown in Figure 7. As expected, the radiation from the telecommunications network when the TK95U cable is used is lower than the radiation from the network when the TK33U cable is used. That is due to the fact that TK95U cable, unlike the TK33U cable, has a sheath (aluminium tape) that reduces unwanted emission from the cable, as presented in Table 1. The highest radiated $E$-field level from the network when using the TK95U cable is measured at 164.8 MHz and is 43.5 dB $\mu$V/m which is 3.5 dB above the limit defined in ITU-T K.60 Recommendation. As it can be seen in Table 2, the number of subcarriers above the proposed limits also decreases compared to the measurement when using a TK33U cable.

The results of $E$-field radiation measurements when the G.fast signal is transmitted through UTP cat.5E cable are shown in Figure 8. It is evident that the radiation from the telecommunications network when using UTP cat.5E is lower than when the TK33U cable is used. These are the results of a cable construction (i.e. lower twisting length), that allows efficient data transmission at a higher frequency and reduces radiation from UTP cat.5E cable. Figure 8 also shows that the radiation from the telecommunications network increases with the increase in the number of twisted wire pairs used. It should be noted that the largest number of twisted pairs of wires in the UTP cat.5E cable is four (eight copper wires). The highest radiation when using one pair of twisted wire is measured at 119.45 MHz and is 41.6 dB $\mu$V/m, while when four pairs of twisted wire are used, the highest radiation is measured at 106.9 MHz and is 47.2 dB $\mu$V/m. Furthermore, when one pair of twisted wires is used, the radiation is 1.6 dB above the limit defined in ITU-T K.60 Recommendation, more precisely, only 9 subcarriers (0.2 % of the total number of subcarriers) have $E$-field level above the limit defined in ITU-T K.60 Recommendation. These results can be used as a good indicator of the radiation that can be expected in user premises given that UTP cat.5E cable is often used for installation of the in-house and the in-building network.

In order to analyse the effect of $E$-field radiation from the telecommunications network when a higher quality cable is used, the G.fast signal is transmitted through an S/FTP cat.7A cable. This cable was developed with strict specifications regarding protection against crosstalk and electromagnetic interference. The S/FTP cat.7A cable has twisted wire pairs that are individually wrapped in aluminium-laminated plastic foil and the entire wires are additionally covered with a common tinned
copper braid. This cable is designed to operate at frequencies up to 1000 MHz enabling 10-gigabit Ethernet connection. The results of measuring the $E$-field radiation from the telecommunications network when using the S/FTP cat.7A cable is presented in Figure 9. As expected, due to the improved shielding of all cables used in this paper, the lower level of $E$-field radiation is measured when an S/FTP cat.7A cable is used. The mean radiation level when using one pair of twisted wires is $\bar{x} = 25.4 \text{ dB} \mu \text{V/m}$ which is 0.9 dB lower than when using a TK59U cable, 2.3 dB when using a UTP cat.5E cable and 7.6 dB when using a TK33U cable with the same number of twisted wire pairs. The highest $E$-field level is measured at 122.8 MHz and is 39 dB $\mu$V/m indicating that all subcarriers are below the limits proposed in ITU-T K.60 Recommendation.

If the wires are not perfectly balanced, due to the introduced differences in the amplitude and phase of the signals in the cable, the common-mode signal will cause an increase in radiation from the telecommunications cable [30]. To simulate radiation from an unbalanced cable, measurement is provided when one of the wires of the twisted pair of wires in the TK33U cable is disconnected, as shown in Figure 2c. The results of $E$-field radiation measurements when TK33U balanced and an unbalanced cable are used compared to the limits defined in ITU-T K.60 Recommendation are shown in Figure 10.

From Figure 10 it can be seen that the $E$-field radiation when using an unbalanced cable is higher than when using a balanced TK33U cable (one pair of twisted wires). In particular, the mean value of the $E$-field radiation, when using a TK33U unbalanced cable is 13 dB higher than when using a TK33U balanced cable. Maximum radiation when using an unbalanced cable is measured at 75 MHz and is 59.8 dB $\mu$V/m, which is 19.8 dB above the limit value defined in ITU-T K.60 Recommendation. According to the results presented in Figure 10 and Table 2, it is evident that the radiation from the telecommunications network when an unbalanced cable is used can cause serious problems with radio signal reception.

Since an unbalanced cable is the result of a faulty cable condition, to prevent radio reception disturbances, the cable must be repaired or replaced as soon as possible.

6 | CONCLUSION

In this paper, the radiation from the in-house part of the telecommunications network when the G.fast2 signal was transmitted through TK33U cable, TK59U cable, UTP cat.5E cable and S/FTP cat.7A cable was measured and analysed. The presented results show that the radiation from the telecommunications network significantly depends on the cable structure used for G.fast2 data transmission, that is, although the electronic equipment is manufactured in accordance with EMC directive, the radiation from the network could be above the defined radiation limits if an inadequate cable is used. This could pose a serious problem in the process of implementing G.fast2 technology as most telecommunications cables already installed in user premises are not designed for data transmission at high frequencies used by G.fast2 technology.

The measurement results showed that the highest radiation level was measured when a TK33U cable was used, while the lowest radiation level was measured when TK59U and S/FTP cat.7A cables were used due to the improved shielding of the cable. In addition, the radiation from the in-house part of the telecommunications network was measured when a TK33U unbalanced cable was used. As expected, the results show that the radiation increases when using a TK33U unbalanced cable compared to using a TK33U balanced cable.

In order to reduce unwanted emission from the wire-line telecommunications network as well as to protect radio services operating in the same frequency range, ITU-T K.60 radiation limits have been proposed. To assess whether or not the radiation from the telecommunications network meets the radiation limits, a comparison between measured $E$-field radiation values and radiation limit values was also made. The measurement results show that only the radiation from the in-house part of the telecommunication network when using a S/FTP cat.7A cable meets the radiation limits defined in ITU-T K.60 Recommendation while the radiation from the network when using other cables is above the limits defined in ITU Recommendation.

This clearly indicates that full protection of radio services is not possible due to the fact that it would require very low
radiation from the network which could not be achieved without significant investment in telecommunications infrastructure. Therefore, in order to ensure coexistence between broadband wire-line telecommunications networks and radio services operating in the same frequency range, effective techniques and methods must be applied to reduce the radiation from the telecommunications network (e.g., notching certain subchannels, reducing power spectral density, etc.).

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