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On Analyzing Video Transmission Over Wireless WiFi and 5G C-Band in Harsh IIoT Environments

JORDI MONGAY BATALLA¹, (Member, IEEE)

National Institute of Telecommunications, 04-894 Warsaw, Poland

Department of Telecommunications, Warsaw University of Technology, 00-665 Warsaw, Poland

e-mail: jordi.mongay.batalla@pw.edu.pl

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ABSTRACT This paper analyzes the quality of Virtual Reality (VR)/Augmented Reality (AR) video streamed in harsh industrial environments. VR/AR is being used in the Industrial Internet of Things (IIoT) as one of the most promising applications for favouring labour conditions and increasing security, while reducing costs of manufacturing. We provide an empirical work that analyzes the impact of industrial environment within the assessment of the video quality transmitted over WiFi and 5G C-band access and discuss the impact of electromagnetic emission of industrial machines in radiocommunications (microwave bands). Even if the presented measurements are limited, they clearly show some aspects of the impact of industrial environments that should be taken into account when developing multimedia IIoT applications. Moreover, we discuss the differences between Radiocommunications technologies for building separated (private) Small Area Wireless Networks (SAWN) for the IIoT in factories.

INDEX TERMS Internet of Things, virtual reality/augmented reality, quality of experience, electromagnetic interference.

I. INTRODUCTION

The Industrial Internet of Things (IIoT) is putting much interest in the use of Virtual Reality (VR) and Augmented Reality (AR) for favouring labour conditions and increasing security, while reducing costs of manufacturing. The condition for the use of VR/AR in IIoT is that the applications will have enough quality to ensure comfort in work.

VR/AR applications have strict requirements for the network and, concretely, they need strict requirements on latency (less than 10 ms is required and around 5 ms is recommended in working conditions) and reliability (five nines in some cases) and, on the other hand, they are data-driven use cases requiring high data rates (around 15 Mbps in Downlink for 4K video and 1 Mbps in Uplink for AR video in standard quality). Moreover, as any application of the IIoT, industrial VR/AR needs very high security assurance.

Taking into account the mentioned requirements, one of the main questions when implementing VR/AR in the IIoT is which network may assure all the requirements, such that VR/AR may be part of the daily industrial activities.

In this paper, we provide an empirical work that analyzes the impact of industrial environment within the assessment of the VR/AR video quality transmitted over WiFi access and 5G C-band access. We also analyze the impact

of electromagnetic emission of industrial machines into radiocommunications (microwave bands). As it is known, the emission of electromagnetic waves (due to the use of many digital circuits in assembly lines) has an impact into the microwave-band transmission. Currently, regulation imposes to industrial machines limitations of electromagnetic emissions up to 6 GHz (e.g., in Europe it is regulated by [1]), however such limitations are per-machine and the final effect of all the machinery depends on concrete environment. Therefore, we use an example industrial environment to measure the impact of machinery into the transmission of critical VR/AR data transmission.

The highlights of this paper are:

- a comparison analysis of WiFi and 5G C-band transmissions of high-bitrate VR/AR with electromagnetic interferences;
- an analysis of *Quality of Service to Quality of Experience* (QoS/QoE) mapping for video transmission in harsh industrial environments;
- a discussion of WiFi and 5G for Small Area Networks in factories.

Our purpose is to respond whether VR/AR may be used in the IIoT in daily work. For this, after the state of the art presented in Section II, we evaluate the impact of electromagnetic noise in industrial environments, which is presented in Section III; afterwards we present a campaign of subjective quality tests of VR/AR video in harsh industrial environment

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and present a model for QoE estimation based on network parameters (Section IV). The obtained results are discussed in Section V under the light of current technological (the introduction of 5G mm-wave) and regulatory (the assumptions for Small Area Wireless Access Points, abbr. SAWAPs). The paper is concluded in Section VI.

II. POSITIONING THE PROBLEM

The assurance of high network QoS is seen as the most successful approach to ensure a good video viewing. The most important network parameters impacting video quality are bitrate, delay, jitter and packet losses. Which ones of them should be analysed depends on the application and the higher layer protocols (TCP vs. UDP, adaptive vs. direct streaming, real- vs. non-real-time, etc.). In the case of IIoT VR/AR, the requirements for the network include high bitrate (video must have high quality for safety reasons), few packet losses (http-based transmission assures retransmission of the lost packets, so the loss of packets impacts into a reduction of bitrate due to retransmission) and very low delay and jitter (real-time transmission).

For given network QoS parameters, many approaches have been adopted to improve the quality of the video transmission at different layers: coding [2]–[4], streaming layer [5], [6] and network [7], [8].

However, QoS does not capture subjective experience of the users when viewing video. Therefore, the introduction of subjective QoE is a more precise approach in order to understand the impact of network transmission into video quality. The problem of subjective QoE is that it is very costly from the point of view of time-consumption and finances, and, because of this, researchers propose models that estimate QoE from the values of QoS [9]. Typically, the Mean Opinion Score (MOS) is accepted as a good and treatable parameter of QoE. In the case of VR/AR, some authors have proposed the Differential MOS [10], [11].

The factors that have impact in the quality of the image perceived by the end user are mainly the video application, the terminal equipment and the parameters of the network transmission [12]. In this paper we are interested in the impact of the industrial environment into the quality of the transmitted video and concretely, we analyse the electromagnetic interferences in industry. Electromagnetic interference does not have an impact into the terminal equipment (we assume that it is perfectly isolated) and is independent of the application. Therefore, as far as application and terminal are concerned, current developed models are valid also in industrial environments (e.g., [12], [13]). However, when we speak about the quality of the network transmission, then the effects of harsh environment into the network parameters are considerable.

III. ELECTROMAGNETIC NOISE IN HARSH INDUSTRIAL ENVIRONMENT

As known, industrial environment is very harsh as far as radiocommunications are concerned. Industrial machinery introduces electromagnetic noise (EMN) that creates

interferences in practically all the current radiocommunications frequency spectrum. The levels of EMN are higher in industrial installations than in other working spaces due to several factors such as: (1) industrial machinery irradiate unintended electromagnetic waves that interfere with radiocommunications emissions; (2) unintended resonance oscillation caused by electrical circuits (however resonance oscillations create waves in a lower bandwidth than the currently used in radiocommunications); (3) electromagnetic fields irradiated by machinery may induce unexpected electric currents in the circuits of antennas creating interferences in the radiocommunications devices. All these effects are called electromagnetic susceptibility of the radiocommunications devices. Electromagnetic susceptibility depends on the frequency and the power of the communication emission.

In the last years, factories are substituting analogical circuits by digital as a natural development of industrial machines. The EMN of digital circuits is much higher than old analogical circuits since the response of digital devices is based on abrupt transitions between 0-level and 1-level, and this provokes emission of electrical signal at many frequencies (many more than the limited frequencies irradiated by analogical devices). Therefore, there is a strong regulation about the electromagnetic noise that any machine can introduce in the environment and this regulation considers emissions until 6GHz [1], however such regulations do not consider the sum of the effects of all the machinery in a close environment.

With the introduction of Industry 4.0 concept, the problem of electromagnetic interference will increase since Industry 4.0 assumes that many of the devices and machines in the industrial environment will be connected wirelessly, so the number of radiocommunications will increase. The radiocommunication waves will multiply the induction effect, which, on its part, creates electromagnetic interferences in a wide frequency spectrum.

Moreover, the future industries are called to include high-performance and high-power machineries, adaptable to a large number of tasks. The electromagnetic interferences will increase in that case since high performance implies more electrical activity and higher signal amplitudes and, as a conclusion, more probability of emitting interferences.

In order to understand the impact of industrial environment into the quality of the VR/AR video perceived by the employees (of the factory), we perform a series of measurements of network parameters (rate, packet loss ratio and latency) under three conditions: (1) when all the industrial machines are off, (2) in the moment when the machines are being switched on, and (3) when all the industrial machines are working in a normal functioning way.

For these tests we prepared continuous download from a server connected near to the radio access point (WiFi or 5G New Radio, 5G NR) to the end device. The WiFi network makes use of 5 GHz bandwidth and the WiFi standard is 802.11ac with 80 MHz channel and QPSK modulation. Since the router is connected by fiber to the WiFi router

(R7800 Nighthawk X4S), we may assume that all the delay is due to the radio connection.

In a second test, we connect the end device through 5G network working on C-band, and concretely, in 3.4-3.48 GHz bandwidth. 5G is in standalone composition, this means that both uplink and downlink are served by 5G NR which is connected to a functionality-limited 5G Core (5GC). The functionalities that our core admit are limited to the uplink and downlink of video connections. The server is located in the 5GC, so that the delay in the fixed network is negligible. The server sends to the terminal 10 parallel multimedia connections, as in the case of WiFi.

The testing tool is able to take information from the very same chipset of the mobile device. This is important in order to obtain values of the network without overhead caused by the application layer. The tool is able to take information from Qualcomm, GCT, Intel, MediaTek, and others and assess quality of service (QoS) in 5G (C-band), LTE, HSPA, WiMax and WiFi connectivity technologies. The advantages of this measurement tool is that we take information at the physical layer just after deciphering messages from the radio interface. The messages are then recorded and can be analysed in real-time or a posteriori. Thanks to that, the load of the mobile device CPU has negligible effect into the measurements. On the other hand, as the messages have been deciphered in the chipset, we can take information from the recorded messages such as signalling (at Layer 1: PCFICH/PDSCH/PUSCH, at Layer 2: PDCP/RLC/MAC, at Layer 3: RRC/NAS), TCP/IP messages and headers of application level messages (voice, video, FTP as well as concrete applications such as Youtube, VR/AR application, etc.).

Fig. 1 shows the values of rate, packet losses and latency (during the test duration) for 1 of the 10 videos downloaded through WiFi connection, whereas Fig. 2 shows the same parameters for 1 video streamed through 5G network. The figures show the network performance when the machinery in the factory is off (before time τ_1 in the figures), the moment when the machines are turning on (between times τ_1 and τ_2) and when the machines are on (after τ_2). The time τ_2 has been selected when the machinery seemed to work with stability.

We can see that bitrate and packet loss ratio are both affected by the electromagnetic interferences provoked by the machines turning on and turned on. In fact, the mean value of the bitrate before τ_1 is 12.8 and 68.7 Mbps for WiFi and 5G C-band, respectively, however after τ_2 the rates are 8.8 Mbps and 59.3 Mbps. Packet loss ratio increases from 7.5×10^{-5} mean value for WiFi connection before τ_1 up to 3.6×10^{-4} after τ_2 (in 5G there are not packet losses in any case).

On the other hand the latency does not suffer significant changes. Let us remark that the latency is measured as the delay of the packet transmission from the server to the terminal (in our testbed server and terminal are perfectly synchronized). We do not consider in this case the delay of the lost packets, so the latency of a packet properly transmitted has not any reason to change in the channel, as it can be

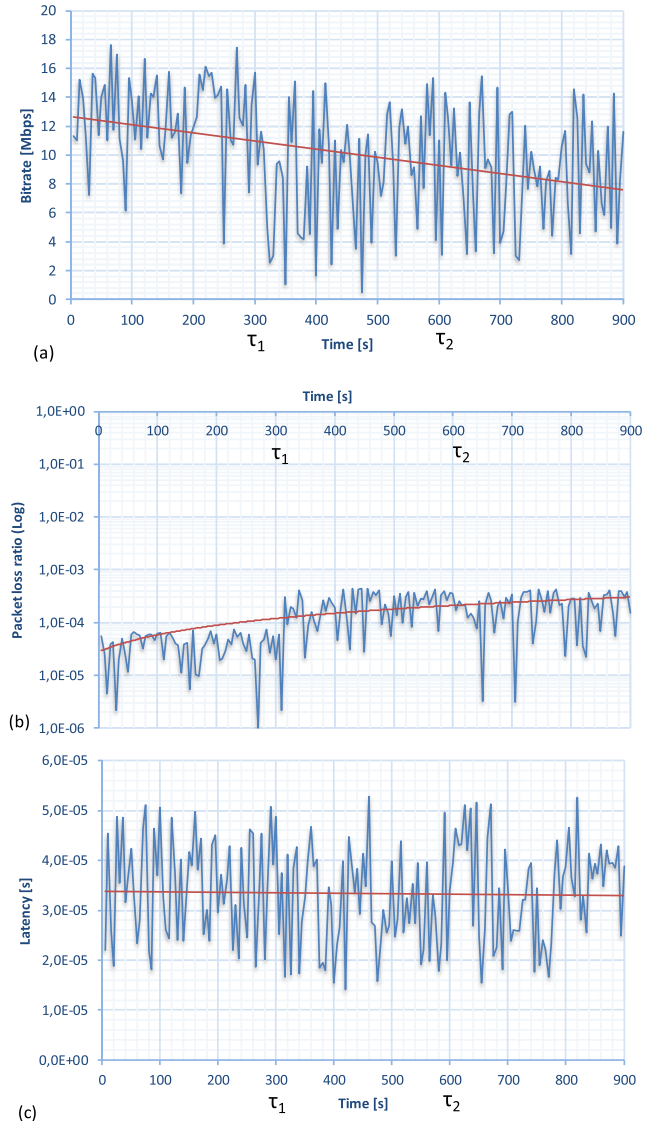


FIGURE 1. Parameters of video transmission over WiFi network: (a) bitrate [Mbps]; (b) Packet loss ratio; (c) Latency [s].

observed in Fig. 1(c). In fact, the mean latencies before τ_1 and after τ_2 , are equal ($34 \mu\text{s}$ and $34.1 \mu\text{s}$ for WiFi and $24 \mu\text{s}$ and $23.9 \mu\text{s}$ for 5G). In our tests, also the jitter did not suffer significant degradation with the switching-on of the industrial machinery. The values of jitter (calculated as the 95-percentile of maximum delay minus minimum delay [14]) before τ_1 and after τ_2 are very similar. This means that, in these tests, electromagnetic interferences do not have impact in the functioning of real-time applications (mainly sensitive to delay and jitter).

The bitrate for WiFi is around 10 Mbps. Let us remark that WiFi router allows for aggregate bandwidth (2.4 and 5 GHz), however one session must be sent in one of the two bandwidths, so aggregate bandwidth is not possible for VR/AR application.

The values of the network parameters for 5G transmission are decisively higher than the WiFi, but this is caused by the

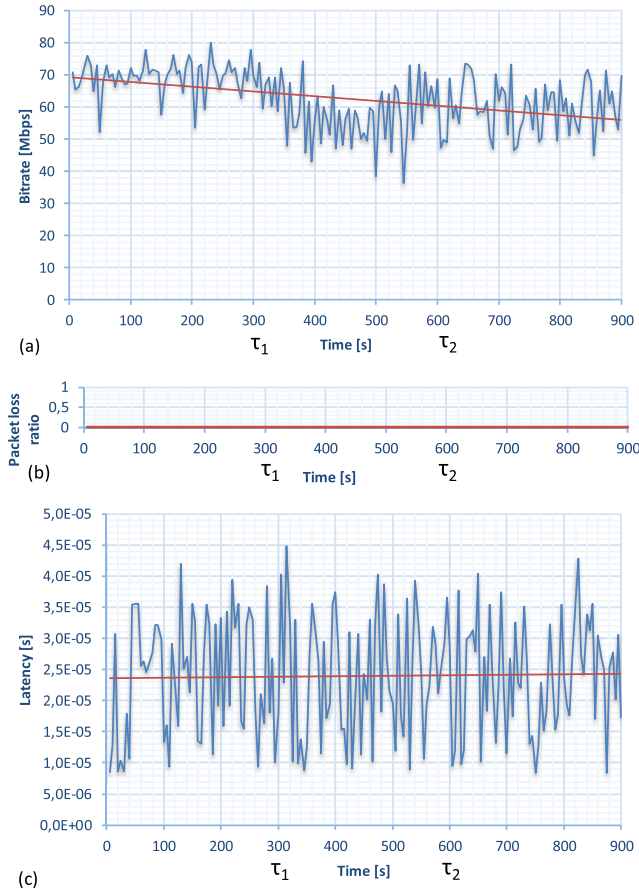


FIGURE 2. Parameters of video transmission over 5G C-band network: (a) bitrate [Mbps]; (b) Packet loss ratio; (c) Latency [s].

fact that the capacity of the 5G network is much higher than WiFi. Moreover, the modulation of WiFi transmission also limits the transmission speed. Simply the two networks cannot be compared in this way, so a discussion on the election of Radio technology to be used in industrial environments will be done in Section V.

IV. ON MEASURING QoE FOR VR/AR VIDEO STREAMED OVER WIFI AND 5G C-BAND

In this section we will understand better the impact of industrial environment when estimating QoE. Since most of VR/AR applications for labour activities in industry do not require audio transmission and are based only on video, we will not consider audio aspects in our model of QoE. In addition, since we are focusing on network degradation, we will not test factors at the application level such as video encoding nor at the terminal level such as VR glasses [15]. Our scope is only to estimate the impact of the network parameters as defined in the previous section.

The existing QoS/QoE models analyse the parameters of the network separately [16]. However, this approach does not take into account the correlation between the network parameters, what implies that small errors in the measurements of one parameter may lead to considerable variations of the estimated parameters and, as a result, the constructed

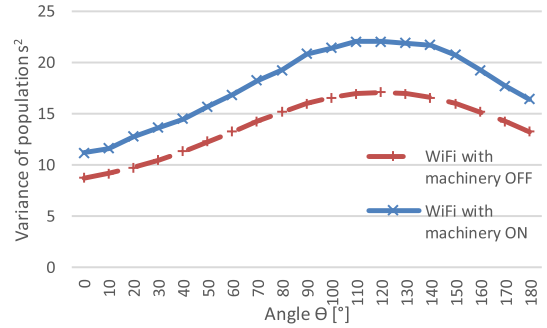


FIGURE 3. WiFi parameters. Variance of the population $[br']$ for different values of angle θ .

model will be instable. Therefore, we propose to analyse the parameters of the network as random variables (r.v.) and to calculate their principal components (p.c.). The p.c. are uncorrelated, which ensures major precision and stability in the model.

A. ON ANALYZING THE NETWORK PARAMETERS

As said before, among the three network parameters that have been analyzed, only two of them are affected by electromagnetic interferences: bitrate and packet loss ratio. The latency is not affected by EMN. Therefore, even if the latency is an important factor impacting the quality of the multimedia experience in VR/AR applications, it is not affected by EMN and known models of QoS/QoE for this parameter can be used.

The first step for estimating QoS/QoE is to analyse the real impact of the network parameters. For this, we consider the two random variables (r.v.), which are bitrate samples, say $[br]$, and packet loss ratio samples, say $[pl]$. We calculate their principal components (p.c.) by doing a linear combination of the two r.v. such that each value of the linear combination br', pl' is:

$$\begin{aligned} br' &= br \times \cos \theta + pl \times \sin \theta \\ pl' &= -br \times \sin \theta + pl \times \cos \theta \end{aligned} \quad (1)$$

With the values of br and pl obtained in the previous section, we may represent the variance of the sample population $[br']$ for different values of θ . Fig. 3 shows the variance of $[br']$ for the samples (WiFi transmission) before τ_1 and after τ_2 (Machinery off and on, respectively). The primary p.c. is obtained for the maximum value of the variance, which is achieved at point $\theta = 120^\circ$. It is worth to remark that this angle is the same regardless of the operation of the machines, which makes feasible to calculate the p.c. independently of the machinery functioning. Obviously, for this angle value, the variance of the second p.c. is minimum, and concretely for $\theta = 120^\circ$, the variance of $[pl']$ is equal to 1.273 when the machinery is OFF and 0.581 when the machinery is ON. The variance of $[br']$ is much higher than $[pl']$ and, therefore, in this case, we may assume that almost all the information about the r.v. is given by $[br']$, whereas $[pl']$ offers small information. This means that the model may be based only

TABLE 1. Parameters of video.

Parameter	Value
Video codec	H.264
Video bitrate	16 Mbps
Video format	2160p (4K)
Video frame rate	50-60 fps

on the first p.c. (i.e., $[br']$). Please, note that in networks we can often reduce the number of p.c. since the parameters are highly correlated.

In the case of 5G network, the losses are null due to high capacity of the network. Therefore, for the scope of these tests, the p.c. of $[br]$ and $[pl]$ are only the values of $[br]$, i.e., $[br'] = [br]$.

B. ON PROVIDING QoE TESTS

In order to provide information on the impact of industrial EMN in QoS/QoE models, we should take into account two main effects, how the QoE changes with variations of the selected p.c. (in our case $[br']$) and which is the effect of the electromagnetic interferences into the network performance and, as a result, into the QoE. These are the two test campaigns presented next.

We provided QoE tests based on 3 min. videos (containing image of the assembly line) captured in the terminal after having been transmitted over the network. The video quality is presented in Table 1.

Once the videos have been captured, we presented the videos to the workers (12 subjects) of the factory and asked the following questions:

- Which is the overall quality of the video (on a 5-point ACR scale, see [17])?;
- Do you see all the details of the assembly line shown in the video (Y/N)?;
- Is the video quality enough for being introduced as a helping tool in daily working conditions (Y/N)?;

In the first test campaign, we enforced the network conditions: download bitrate and packet loss ratio (the rejection of given packet was selected randomly), so that the values of br' were well-known. The responses to the first question for different br' (br' has been normalized to values from 0 to 1) are presented in Fig. 4 in the form of Mean Opinion Score (MOS). Each MOS value is the average of the opinions of the 12 subjects. The figures present also the confidence intervals (at a 0.95 confidence level) but they are very small to be appreciated clearly.

From the results of Fig. 4 it is easy to model the behavior of subjective MOS in relation to br' . This model is also presented in Fig. 4, i.e., $MOS_{max} - a_1 \cdot \exp(-a_2 \cdot br')$. This will be explained in detail in the next sub-section.

The responses to the second and third questions were, at first glance, contradictory since the majority of subjects responded that it was possible to see all the details of the assembly line (only 3 subjects responded 'No' in the second test, i.e., when the industrial machinery was on),

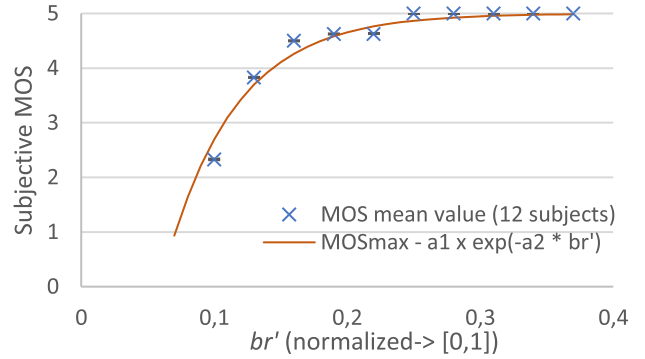


FIGURE 4. Subjective QoE test results for increasing values of br' .

TABLE 2. QoE tests results with 0.95-level confidence intervals.

Video	MOS Chunk#1 (1-10 s)	MOS Chunk#2 (10-20 s)	MOS Chunk#3 (20-30 s)	MOS Chunk#4 (30-40 s)	MOS Chunk#5 (40-50 s)
WiFi: Video#1 (machines off)	4.1±0.4	3.8±0.5	4.0±0.4	4.15±0.4	3.8±0.5
WiFi: Video#2 (machines on)	2.8±0.6	2.8±0.6	4.1±0.8	3.0±0.4	2.6±0.6
5G: Video#3 (machines off)	5.0±0.0	5.0±0.0	5.0±0.0	5.0±0.0	5.0±0.0
5G: Video#4 (machines on)	4.9±0.0	5.0±0.0	5.0±0.0	4.9±0.0	5.0±0.0

however most of the subjects responded negatively to the third question. The motives could be very variate, but we point out the psychological influence, since at this point the workers realized that they should work in different conditions as they usually did, what could impact negatively in the responses.

The second test campaign aims to model the impact of the interferences of industrial machinery into the QoE results. The campaign is based on 3 min. videos downloaded in the network conditions presented in previous section. The video is captured in the terminal in both cases: when the machines are on and when they are off (for the scope of QoE tests, we discarded the video captured during the turning on of the machines).

The values of the QoE tests for the first question are presented in Table 2. The first line corresponds to the scenario when the video is transmitted by WiFi network and the machines are switched off, whereas the second line includes the scenario with the video transmitted by WiFi when the machines are on. The third and fourth scenarios are for 5G transmission for machines off and on, respectively. The 3-minutes video has been cut off in 36-seconds chunks, so each scenario includes five QoE tests. Let us remark that, for each one of the chunks, the starting buffer of the client application was empty.

The application of ANOVA method showed that the average values of the tests for scenario 1, 3 and 4 are statistically equivalent, however the ANOVA showed an irregularity in scenario 2 due to Chunk#3 test (bolded value in the Table). The cause is difficultly understandable. If we

ignore Chunk#3 test, then the MOS values of the other 4 tests are statistically equivalent. From the test results shown in Table 2, we may conclude that the electromagnetic noise of the factory has a significant impact into the quality of the video experienced by the factory employees in scenario 1. 5G scenario does not suffer degradation since 5G bitrate is much higher than the video bitrate, even when there are interferences.

C. ON IMPROVING QoS/QoE MODELS IN HARSH INDUSTRIAL ENVIRONMENT

We are now discussing how to model the subjective QoE from the values of objective QoS of the network.

From the results provided in previous sections, we may conclude the following:

- Electromagnetic interferences cause a diminution of the bitrate and an augment of packet losses, whereas they have not impact into the latency (see Fig. 1 and Fig. 2);
- It is possible to calculate the principal components of the network parameters (QoS parameters), such that the p.c. are uncorrelated. The p.c. are independent of the impact of the electromagnetic interferences (see Fig. 3). In general, it is possible to reduce the number of p.c. since only one or few of them give most of the information about the network parameters;
- It is possible to model the QoE based on p.c. of the network parameters, which offers major precision and stability in the model than in the case of models based directly on the network parameters (see Fig. 4);
- It is possible to calculate the degradation factor (call $degr_{EMN}$) due to EMN in the environment as the relation between the average value of the main p.c. of the network parameters when the machines are switched-off (br_{OFF}, pl_{OFF}) and when they are switched-on (br_{ON}, pl_{ON}), as follows:

$$degr_{EMN} = \frac{br_{OFF} \times \cos \theta_{max} + pl_{OFF} \times \sin \theta_{max}}{br_{ON} \times \cos \theta_{max} + pl_{ON} \times \sin \theta_{max}}, \quad (2)$$

where θ_{max} is the angle of maximum variance of populations (see Fig. 3). It is worth to remark that $degr_{EMN}$ can be calculated by providing low number of measurements.

In Fig. 4 we may observe that MOS (subjective Qoe) has an exponential behaviour in relation to mean values of br' . As we reduced the number of network parameters to one main p.c., then the degradation of the video quality due to the network (call $degr_{NET}$) may be defined as in formula (3).

$$degr_{NET} = a_1 \times \exp\left(-a_2 \times \frac{br'}{f_{e,n}}\right), \quad (3)$$

where br' is the p.c. of the QoS parameters measured without electromagnetic noise. The factors a_1 and a_2 depend on the concrete network conditions.

In this case the QoE may be estimated as $MOS_{max} - degr_{NET}$.

The exponential behaviour of the curve agrees with other QoS/QoE models of the literature. One of the most complete

test campaigns of video QoE was performed by ITU-T Study Group No. 12, which proposed a model inherited from the E-model proposed in telephony [13]. In such a model, they defined the packet loss robustness factor for video quality as:

$$D_{pplV} = \alpha + \beta \exp\left(-\frac{Fr_V}{\gamma}\right) + \delta \exp\left(-\frac{Br_V}{\varepsilon}\right), \quad (4)$$

where Fr_V is the video frame rate, Br_V is the video bitrate and $\alpha, \beta, \gamma, \delta$ and ε are values that depend on the concrete transmission.

As a conclusion, our estimation of QoE is obtained by making the following steps: (i) to measure the network parameters; (ii) to calculate the p.c. of the measurements; (iii) to reduce the number of p.c.; (iv) to calculate the parameter $degr_{EMN}$ by applying formula (2); and (v) to calculate the QoE value by applying the formula (3).

V. DISCUSSION ON RADIO TECHNOLOGIES IN SMALL AREA INDUSTRIAL NETWORKS SUCH AS FACTORIES

In this chapter, we will discuss the differences between radiocommunications technologies in the framework of industrial factories. With the development of Industry 4.0 concept, there have increased the requirements of the network technology in regards to volume of traffic, volume of connections, maximum delay and security assurance. The general approach is to build separated Small Area Wireless Networks (SAWN) inside the factory, so that many of the security issues may be solved thanks to the separation of the radio and network resources.

There are different Radio technologies that can afford separate SAWN with reduced coverage. The main difference comes from the use of licensed or unlicensed bandwidth. Unlicensed bandwidth is cheaper, however the technologies are more vulnerable to interferences (the bandwidth may be used by anyone) and to security (in licensed-bandwidth transmissions security keys are written in the hardware or are written electronically on a per-user basis, e.g., in eSIM cards).

The results of the bitrate of 5G C-band and WiFi shown in Fig. 1(a) and 2(a) show a clear commanding position of 5G over WiFi, however there are many objections to such a conclusion. From the technological point of view the tests show a very favourable situation of 5G transmission since there is only one communication in the 5G cell, which is an exceptional situation. Moreover, we can think many other factors that should be taken into account before deciding about the network technology to be used in a given environment. Among these other factors, there is the latency of the network. One of the requirements of VR/AR applications is the necessity of low latency, which can be only achieved by locating the video-processing server close to the end user. This approach is known in mobile networks as Multi-access Edge Computing (MEC), however MEC is not yet deployable in 4G and only the 5G will make MEC feasible [18]. In unlicensed wireless access, the issue is much easier,

since the network implementing VR/AR can be virtually or physically separated from the Internet and everything can be developed into the local access network.

Unlike 4G, the new 5G technology provides several mechanisms that make feasible the creation of ad-hoc private small networks [19], which are required by many localized or site-bound applications such as industries. For this, Radio Access Network (RAN), called New Radio, and Core Network (5GC) should be deployed in the private network. One of the most important features for making this possible was the virtualization of the Distributed Unit (DU), which is the radio unit responsible of the information sent to the air interface. Virtualization is possible thanks to the clear separation of the software and the hardware functions, which is in the essence of 5G, so the vendor-agnostic commercial off-the-shelf (COTS) hardware makes different software ecosystems feasible. The idea is to create virtual RAN and virtual 5GC, which are deployable in a wide range of hardware while avoiding strong performance restrictions. Virtual Core with limited functionalities and virtual Radio with limited performance can be developed as a practically isolated private network.

Private networks built in 5G break down one of the most important “forbidden subjects” in the previous generations of mobile networks, which practically located all the solutions in the cloud, constraining, in this way, that the provider of the service had to be a third party with her/his resources centralized somewhere in the cloud, and the network had to ensure the strict requirements of the service. On the other hand, in local network with unlicensed access, the resources for implementing the service may be situated physically in the industrial installation.

Since 5G standard has assigned 3.4-3.8 GHz for most of the wide coverage applications, it is logical to think that 26 or 28 GHz (it depends on the country regulation) is the most suitable frequency for small area private networks. Just like that 3.5 GHz is used primarily for Business-to-Customers, 26 GHz may be used for Business-to-Business, with special interest to Industry 4.0, since higher frequencies suffer lower interference in harsh environments.

There is a last aspect that should be taken into account in order to select properly the Radio technology inside a factory. This is the regulation that makes legal the use of antennas. In the last years, there is a strong intention of facilitating the development of SAWN developed by Small Area Wireless Access Points (SAWAPs) with limited power emission. The reason is that these antennas emit limited electromagnetic fields and are safer for human-beings and animals (the general rule is the so-called ALARA rule: “As Low As Reasonably Achievable”). The SAWAPs are normally separated in three categories, depending on the maximum allowed power: 200 mW, 2W and 10 W. If we consider small and medium size spaces, access points should have a maximum power of 200 mW or 2 W (E0 or E2 classes), however, in the case that until 10W-power antennas (class E10) are needed, then other requirements about the physical space may apply.

E10 antennas are addressed to a number of users between 100 and 2000 with a maximum coverage between 200 m and 2 km [20].

VI. CONCLUSIONS

In this paper we showed the impact of the harsh industrial environment into the transmission of VR/AR video used in IIoT applications. After comparing network measurements in absence and presence of electromagnetic noise, we discussed the impact of the noise into the video quality and, specifically, into the models of subjective QoE

At the end of the paper we introduced a discussion about the technologies used in the future private networks in industries. WiFi and 5G are both improving current technological solutions, so that scenarios as VR/AR should be normally seen in a close future.

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JORDI MONGAY BATALLA (Member, IEEE) received the M.Sc. degree from the Polytechnic of Valencia, Spain, and the Ph.D. and D.Sc. degrees from the Warsaw University of Technology, Poland. He is currently the Deputy Director of Research with the National Institute of Telecommunications, Poland. He is also an Associate Professor with the Department of Computer Network and Services, Warsaw University of Technology. He participated (coordination and/or participation) in more than 30 national and international ICT research projects (including EU ICT Programmes). He is an editor of four books and author of more than 150 articles published in books, international journals, including the *IEEE Communications Magazine*, the *IEEE WIRELESS COMMUNICATIONS*, the *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS*, *ACM CSUR*, and so on, and conference proceedings and patents (Polish and European Patent Offices). His research interests include technologies (radio: 5G and 6G, core: Network services chain, SDN, AI) and applications (DLT and blockchain, the Internet of Things, smart cities, multimedia) for the future Internet. He is a Technical Member of the European Blockchain Services Infrastructure (European Commission). He is also a member of Hyperledger platform (a TheLinuxFoundation project) and the Polish Normalization Committee and collaborates actively with ITU-T Standardisation Groups (SG-12). He is/has been a guest editor and member of the Editorial Board in more than ten international journals. He is an adviser in different international and national technical groups. He is also a Technical Adviser of the Polish Government for 5G cybersecurity law, the Polish Ministry of Infrastructure for Autonomous Automotive, and others.

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