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Testing of VoLTE Mean Opinion Score in Reverberation Chambers

Massimo Barazzetta¹, Michele Colombo¹, Luca Bastianelli^{2*}, Franco Moglie², Valter Mariani Primiani², Riccardo Diamanti³, Davide Micheli⁴

¹ Nokia Networks Italia, Energy Park 14, 20871 Vimercate, Italy

² Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, via Brecce Bianche 12, 60131 Ancona, Italy

³ TIM S.p.A., Via Guido Miglioli 11, 60131 Ancona, Italy

⁴ TIM S.p.A., Via Parco de' Medici 69, 00148 Rome, Italy

* E-mail: l.bastianelli@pm.univpm.it

Abstract: In this paper, we present results of a call testing campaign using voice over long term evolution (VoLTE) technology on the radio access network of the operator Telecom Italia mobile (TIM) – Telecom Italia Mobile. The quality of the voice call is expressed by means of the mean opinion score (MOS). The electromagnetic propagation environment has been reproduced within a reverberation chamber, and its effect on MOS has been evaluated by varying the signal strength, i.e. the reference signal received power and the signal to interference noise ratio. The aim is to find a correlation between the radio propagation environment and the perceived quality of the speech. Regardless of the networks technology, voice quality could be impacted by several factors: traffic load of LTE evolved Node B, quality of service, radio pathloss, mutual radio interference, multipath, etc. Interference and multipath are added to the useful signal in order to deteriorate the MOS, until the VoLTE calls dropped. Target of such work is to properly set the thresholds that trigger a handover of single radio voice call continuity to other radio access technologies (UMTS or GSM). Tests take also into account the adaptive multi-rate CoDec selected by the network.

1 Introduction

Mean opinion score (MOS) provides a ranking of speech quality based on the determination of the level of impairments introduced by a transmission system. MOS is applicable to several scenarios, where a voice call could be established among mobile phones, fixed phones and also computers, as far as these elements are interconnected. It is a measure that represents the quality experienced by the user to the evaluation of voice and video intelligibility. It provides a ranking criteria in the range from 1 to 5, where the lowest value stands for bad quality, whereas the highest value means excellent [1], see Table 1. Rank 1 corresponds to scenario where very annoying impairment turns into bad quality, on the contrary rank 5 index an excellent situation, where impairments are negligible. Although the classes correspond to an integer, the MOS is reported as a real value to account intermediate cases.

In the present campaign, MOS has been measured by means of perceptual objective listening quality analysis (POLQA) algorithm [2]. As inputs, POLQA receives two waveforms represented by two data vectors. The first contains samples of the undistorted reference signal, the second the degraded signal of the receiving entity. MOS calculation by POLQA is based on comparing these two waveforms, as described in [2].

The radio environment has been reproduced in a reverberation chamber (RC). This is a resonant enclosure that operates at a frequency band where a large amount of modes are excited at the same time. The field obtained in this overmoded condition is statistically uniform, isotropic and without a preferable polarization [3, 4]. This is attained by using an adequate field stirring process in a typical rectangular cavity or in a more complex cavity shaped, e.g. including curvature, diffusers or by using non parallel walls [5, 6]. This condition replicates common cellular network scenarios, where the electromagnetic field is scattered and stirred by complex structures and moving objects [7, 8]. It was used for testing LTE wireless communication systems [9] or testing wireless devices [10, 11]. Moreover, in conjunction with a Doppler effect simulator, it was also used to investigate LTE users on high-speed trains [12, 13]. By inserting an adequate amount of absorbing material [14, 15], an

RC can be used to replicate different propagation environments [16–18]. Thanks to these expedients, a controllable direct over diffuse received energy is achieved [19]. The RC is also present in the 3GPP test specifications. For example, the TS34.114 [20] includes RC in the certification testing of handsets as one of the methodologies for total radiated power (TRP) and for total isotropic sensitivity (TIS). 3GPP also refers to MOS as a recognized method to score speech quality, as indicated in TR26.975 [21].

RC tests have been extended to last generation of LTE terminals [22] by using an LTE base station simulator. Recently, a complete set of over-the-air (OTA) tests have been carried out adopting a commercial LTE base stations (BS) which radiates the signal in an RC that reproduces well known propagation environments (as the ones described in [23] and [24]). The performance was observed on downlink (DL) LTE single carrier throughput [25], uplink (UL) LTE throughput [26], and DL LTE throughput in carrier aggregation scenarios [27].

These were actually the first attempts to use real live BS instead of a BS emulator. Likewise [23–27], this paper exploits the commercial LTE BS of Nokia Network Italia to assess the performance of VoLTE services. To this ground, typical propagation environments such as indoor/outdoor locations or commercial/residential settlements (please refer to [23] and [24]) are reproduced in the in-house RC of the Università Politecnica; hence typical values for the delay spread, decay time and Rician K-factor are generated.

The impact on MOS by different reference signal received power (RSRP), signal to interference noise ratio (SINR), chosen CoDec [21] and propagation environments is analyzed. Wherever possible, an indication on how quality perceived by the user could be enhanced through network optimization will be provided.

The original idea behind this work was to evaluate any potential impact of the radio propagation environment (described by parameters like the power-delay profile) to the quality perceived by the VoLTE user. Note that, even if it is a long time that VoLTE is in use in mobile operator's network around the world, these concepts are also valid in the outlook of 5G. 3GPP NSA-3x solution, which is available right now, normally offload only data traffic to 5G leg, while IMS signaling and VoLTE call is maintained on the 4G leg. Thus, the

Table 1 MOS classification.

MOS	Quality	Impairments
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

conclusions we came across in the paper are applicable also to the case of 5G, until (at least) a 3GPP 5G standalone solution will not be available. Finally, reverberation chamber (RC) was used to replicate different multipath conditions easily, introducing/removing absorbing panels from it, based on replication of RC parameters (like power delay profile) which are typical from indoor and outdoor environment as reported in the literature. In order to come to similar results, normally operators have to run expensive drive test campaigns that require time, personnel, tools and money.

Tests have been executed in cooperation between TIM, Università Politecnica delle Marche and Nokia.

2 Setup Description

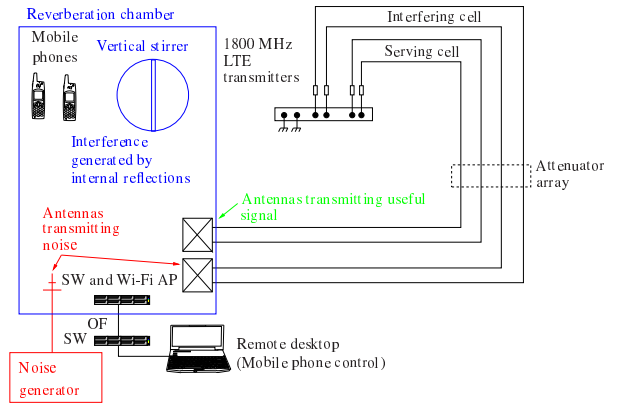
OTA tests were performed inside an RC with dimensions $6 \times 4 \times 2.5 \text{ m}^3$, equipped by a z-folded vertical stirrer having a rotation diameter of 1.5 m and a height of 2.4 m, and a horizontal stirrer that was stationary and absorbing material. Figure 1 summarizes all connections among adopted instrumentation. A NOKIA base station (BS) model Flexi Multiradio 10 feeds the chamber through an array of precision electronic attenuators (R&S HOSM 2×4) connected to two antennas (Kathrein 80010454) in the band of 1 800 MHz.

Two mobile phones are controlled by a remote desktop placed outside the chamber. Mobile phones are provided by software (Nemo Handy) that allows us both control phones and collect diagnostics data of the wireless connection outside the chamber by using a remote desktop. The POLQA was integrated in this tool. We did the measurements without modify the POLQA implementation and parameters. The connection between remote desktop and mobile phones is due by Wi-Fi connection inside the RC whereas an optical fiber (OF) connects the remote desktop – via a switch (SW) – to a Wi-Fi access point (AP). Two LTE transmitters are connected to two antennas, one is the serving cell which injects the useful signal. The other one is the interfering cell that injects the noise signal. In addition, a second white noise generator was added.

By changing the power of the noise generators, we can set the SINR to the desired value. However, the SINR is not constant because it also depends on the intrinsic behavior of the chamber. The chamber is properly lined by absorbing anechoic panels in order to reproduce a well known multipath environment in terms of power delay profile (PDP) [23, 24].

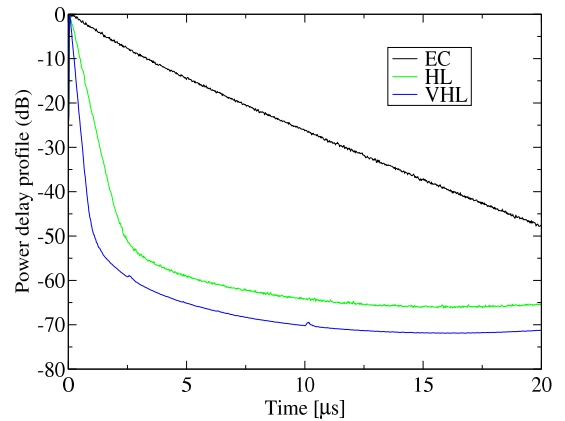
Figure 2 shows typical power delay profiles reproduced in RC, for various loading conditions (number of panels) inside the chamber. The number of absorbing panels, and their placement, were chosen after several attempts until the τ_{RMS} match values reported in the standards [15, 26, 28, 29]. Table 2 reports the evaluated root mean square of the time delay spread (τ_{RMS}) for the configurations considered in Fig 2. Each antenna panel contains two cross polarized antennas operating in the range 1 710-2 180 MHz. The two mobile stations, Samsung S7, running VoLTE calls through automatic scripts, were connected simultaneously to the LTE network and to a WiFi access point, providing physical connectivity for remote control of the mobile stations from a laptop positioned outside the chamber.

Figure 3 depicts the outer view of the RC setup. Figure 4 shows RC configurations that emulate the propagation environment.

**Fig. 1:** Test environment setup.**Table 2** Evaluated τ_{RMS} for loading scenarios considered in Fig 2 and ratio between the volume of the absorbers and the total volume of the RC.

Configuration	τ_{RMS} (ns)	Volume ratio (%)
Empty chamber (EC)	1 347	0
High load (HL)	163	0.27
Very high load (VHL)	67	0.53

- Outdoor replication: RC equipped with 2 Emerson & Cuming VHP-8-NRL panels + 5 Emerson & Cuming ANW-77 panels (positioned on the floor): high load (HL) condition: stirrer rotating at 30 deg/s.
- Indoor replication: RC equipped with 2 Emerson & Cuming VHP-18-NRL panels + 5 Emerson & Cuming ANW-77 panels (positioned on the floor) + 8 Emerson & Cuming VHP-8-NRL panels (positioned vertically) very high load (VHL) condition: stirrer rotating at 60 deg/s.

**Fig. 2:** Power delay profile for each chamber loading condition: EC, HL and VHL.

The rotation speeds were set in order to replicate the fast Fourier transform (FFT) of the RSRP time variation recorded in outdoor and indoor environments during drive test campaigns performed on the TIM live network. The choice of 30 deg/s and 60 deg/s get as the best stirrer rotation speeds to replicate RSRP fluctuations of signals recorded in live network. FFT analysis is reported in Fig 5, for example for outdoor scenario.

MOS has been measured at different RSRP conditions that was set by attenuator array: starting from -95 dBm , down to -110 dBm , -115 dBm , -120 dBm and adding both modulated interference from a neighbor cell and white noise.

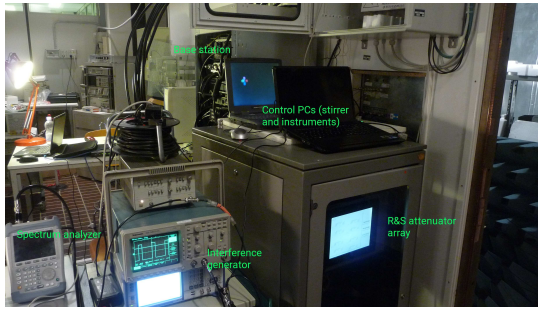


Fig. 3: Picture of the outer view of the RC.

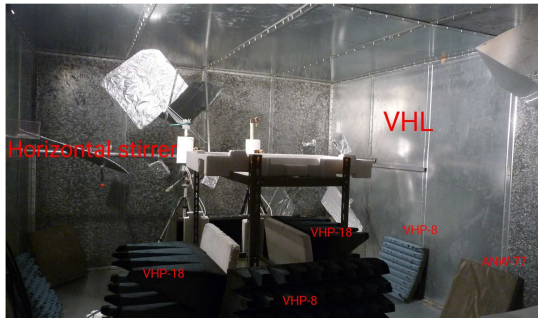
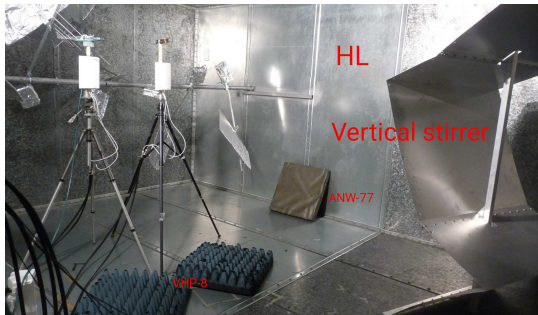


Fig. 4: Inner views of the RC for HL (top picture) and VHL (bottom picture) scenarios. The horizontal stirrer was stationary and operated only as diffuser during measurements. The kind of absorbers placed within the RC are labeled for a better comprehension.

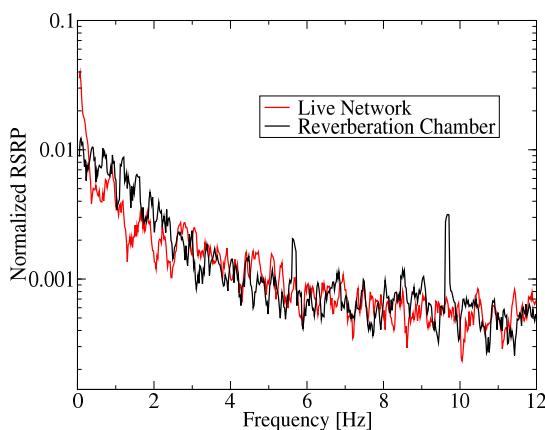


Fig. 5: Fast Fourier Transform (FFT) of RSRP recorded in RC compared with FFT of RSRP recorded in live network, outdoor environments.

3 Measuring MOS in reverberation chambers

This paper presents a procedure (based on FFT) to reproduce multipath environments which are typical of radio cellular networks

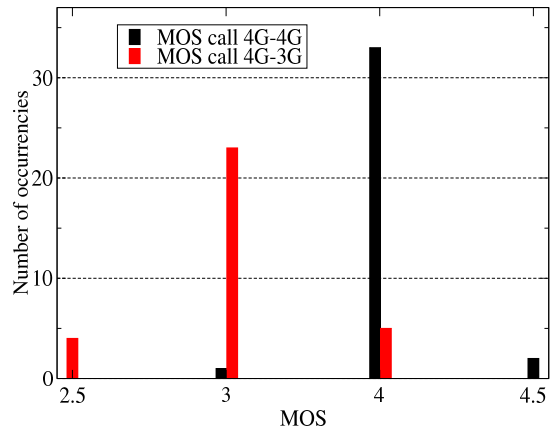


Fig. 6: MOS histogram vs CoDec bitrate for 4G-4G call (23.85 kbps CoDec) and 4G-3G call (12.65 kbps), in the reproduced outdoor propagation environment.

and to evaluate their impact over the voice quality perceived by the user, executing VoLTE calls between users positioned within RC. The results reported hereafter demonstrate the robustness of adaptive multi-rate (AMR) CoDecs used in VoLTE technology. The AMR codec is an audio compression format that is optimized for the speech coding, adopted by the 3GPP. In fact, despite a weak signal strength and the addition of multipath and interference, they are designed to maintain a good quality perception even in very poor radio conditions. It will be show that the MOS is almost independent from multipath. Nevertheless, it is also reported how much the MOS is dependent on the CoDec used in the VoLTE call. In VoLTE, even if all the possible CoDecs are supported both by user equipment (UE), radio base station (BS) and LTE core network called evolved packet core (EPC), these are determined in the initial phase of call setup during the session initiation protocol (SIP). They are chosen on the basis of the radio technology used, i.e. depending on the CoDecs supported by the radio access technologies – like 4G, 3G, 2G or public switched telephone network (PSTN) – used on the other ends. For example, possibilities are:

- 4G-4G call: AMR-WB (wideband), 23.85 kbps;
- 4G-3G call: AMR-WB, 12.65 kbps;
- 4G-2G call: AMR-NB (narrowband), 12.2 kbps.

For example, number of MOS occurrences for a 4G-4G call (both users inside RC) and 4G-3G call (just 4G user inside RC) are reported in Fig 6. Average MOS for 4G-4G call is 3.71, while average MOS for 4G-3G calls is 3.24. This means that the CoDec bitrate is the first factor affecting MOS, rather than radio conditions.

Indeed, MOS behavior against SINR shows how MOS does not change significantly when SINR deteriorates, contrary to the packet data throughput. MOS is maintained up to good values (close to 4) until SINR drops to very low values (around -8 dB), as it is reported in Fig 7 for a 4G-4G VoLTE call in an outdoor environment. With values lower than -8 dB, MOS suddenly drops and a radio link failure (RLF) occurs.

The behavior is similar, when the same test is repeated with different signal strengths (-100 dBm to -115 dBm) and in different propagation environments (indoor). Also the activation of some features like discontinuous reception (DRX) or transmission time interval (TTI) bundling does not present valuable impacts on MOS in the radio conditions analyzed in present paper. When representing the MOS values over a scatter chart against SINR, the distribution of samples shows how MOS degrade only for very low SINR values. Simultaneously, the growing of standard deviation (more spread dots corresponding to low SINR values on chart) indicates some variation in the quality perceived by the user.

Moreover, Fig 8 reports the MOS when an indoor scenario was replicated. The voice quality does not depend on the scenario thanks to the AMR CoDecs.

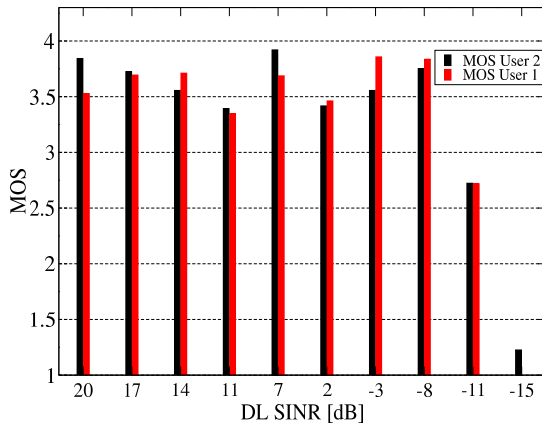


Fig. 7: MOS for 4G-4G call (23.85 kbps CoDec), vs DL SINR reproduced outdoor propagation environment. MOS is averaged on multiple tests.

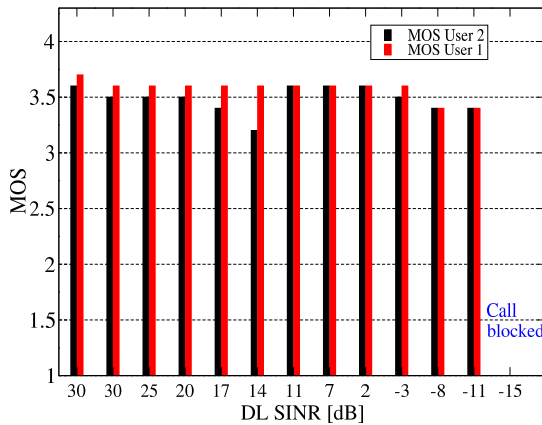


Fig. 8: MOS for 4G-4G call (23.85 kbps CoDec), vs DL SINR reproduced indoor propagation environment. MOS is averaged on multiple tests.

4 Measuring MOS with continuous calls

In previous section it is explained how much MOS is dependent on the chosen CoDec bitrate (AMR-WB, AMR-NB) and how much is independent from the radio conditions and from the propagation environment (until a dropped call occur). MOS was measured between a called and a caller party, running repetitive calls. In this section, MOS measurements running continuous calls will be describe, reducing signal strength and increasing interference. The aim is bringing the UE down to the RLF with a drop call. In Fig 9, MOS as a function of SINR in DL is reported.

The scenario reproduced for the radio propagation is an outdoor environment with -110 dBm average RSRP level. MOS becomes more unstable when SINR is downgrade lower than -5 dB. We varied the MOS reducing it to the sensitivity limit of the receiver.

In this scenario, a user camped on a 4G cell (placed within the RC) makes a continuous call to a user located outside RC, and camped on a 3G (see Fig 10) and 2G (see Fig 11) network. MOS is reported for different RSRP values. In particular, DL SINR is decreased by injecting noise, until a VoLTE dropped call occurs. For each RSRP-SINR pair, the call drops when SINR becomes lower of its working threshold and the call drops do not depend on the time, being the RC a close and reproducible environment. The plot shows that MOS remain around the value of 3 which is an acceptable value until RSRP is -124 dBm and DL SINR is 0 dB. The lower the RSRP, the higher the SINR allowed until the VoLTE drop call.

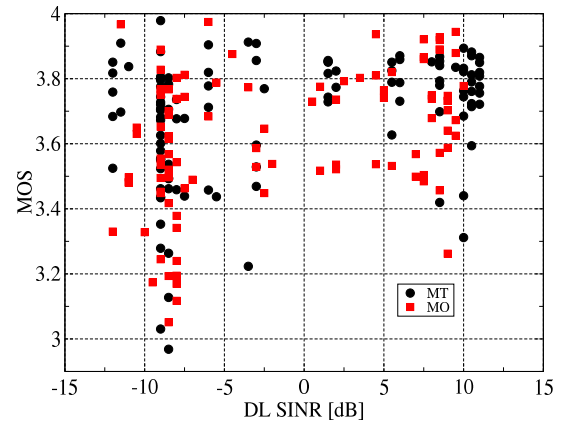


Fig. 9: MOS measurements in continuous call mode for 4G-4G call (23.85 kbps CoDec), vs DL SINR reproduced outdoor propagation environment for the mobile terminated call (MT) and for the mobile originated call (MO). Both for MT and MO, RSRP = -110 dBm

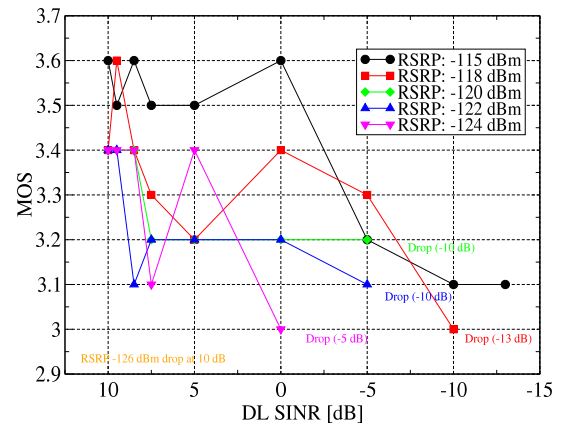


Fig. 10: MOS measurements in continuous call mode, for different values of RSRP, vs DL SINR. The end of each line correspond to a dropped call. 4G-3G call (AMR-WB CoDec, 12.65 kbps, 16 kHz sampling).

Results in Fig 10 Fig 11 refer to only one call, for a pair of RSRP and SINR. Severe MOS tests have been done during a single call setup. A MOS test is approximately six seconds long and the duration of a single call is two minutes.

Beyond this limit (-126 dBm), call is dropped as useful signal is too low. Fig 11 shows results for the 4G-2G call. In this case, the CoDec (AMR-NB, with 8 kHz sampling bitrate and 12.2 kbps data bitrate) is adopted and the MOS starts immediately from a value lower than 3 - that means, annoying impairments on speech quality.

Also in this case, while the absolute values of MOS are lower than the ones in Fig 10, dropped calls occur almost at the same values of SINR and RSRP. Based on these results, a 4G users running VoLTE all may stay camped on LTE until the RSRP remains higher than -124 dBm and if the SINR conditions are good enough. Beyond this limit, a RLF will most likely occur with a drop call.

5 MOS Distribution Against CoDec Rate

The CoDec bitrate adopted by the VoLTE call depends on UE, radio base stations, and EPC capabilities. This information is exchanged between these network elements at VoLTE call setup (SIP signaling). Since, normally, voice over LTE may support all possible coding bitrates (AMR-NB and AMR-WB), the CoDec bitrate that is finally chosen depends on the capabilities of the other end. Whatever it is: GSM (2G), UMTS (3G) or PSTN user. From the analysis, the coding

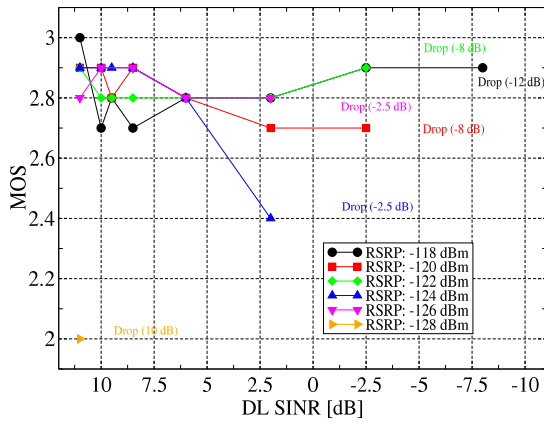


Fig. 11: MOS measurements in continuous call mode for 4G-2G call (AMR-NB, 12.2 kbps, 8 kHz sampling), of as a function of different values of RSRP, vs DL SINR reproduced outdoor propagation environment.

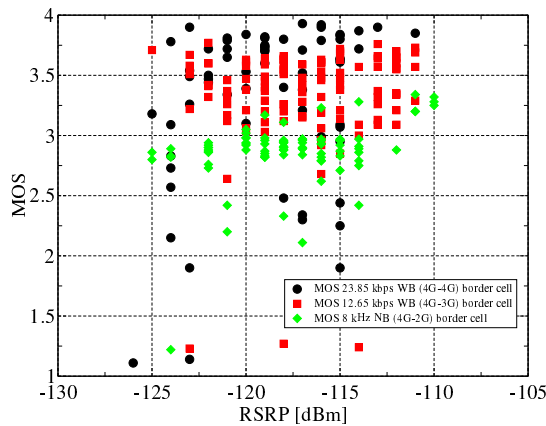


Fig. 12: 4G-4G, 4G-3G, 4G-2G call MOS at cell edge, vs RSRP, continuous call.

bitrate is the most impacting factor for MOS. Fig 12 shows a distribution where all the recorded samples for 4G-4G, 4G-3G and 4G-2G calls are plotted as function of RSRP and reference signal received quality (RSRQ) at cell-edge conditions. The number of samples was around 100 for each case. In this way, it is possible to analyze how to set thresholds to UMTS or GSM of single radio voice call continuity (SRVCC), being these thresholds expressed against serving cell RSRP and RSRQ. Charts in Fig 12 and Fig 13 show that there are no valid MOS measurements for $RSRP < -126$ dBm and $RSRQ < -23$ dB; thus, triggering thresholds for SRVCC handovers should be set higher than these values. As expected, in Figs. 12, 13 the AMR-WB with the higher bitrates improves the perceived speech quality w.r.t. the AMR-NB due to its wider speech bandwidth.

6 Summary of main results

After having run the tests, it turned that the quality was almost non-variant against deterioration of radio quality (SINR, RSRP), until it was not suddenly dropping with a radiolink failure. In the paper, we mentioned that outdoor and indoor propagation environments were reproduced inside RC, but only the outdoor cases are reported in charts. This because - once again - the AMR CoDecs were not influenced at all by different multipath conditions. In order to demonstrate this, we add also a chart showing MOS against DL SINR in poor radio conditions ($RSRP = -110$ dBm) and similar DL SINR of the one reported in Fig 9. In these conditions, we have degraded the SINR until a radiolink failure was not observed. Having explored, thanks to the RC, different propagation conditions (in

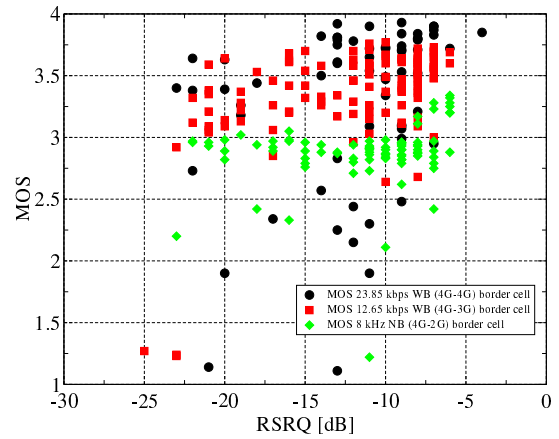


Fig. 13: 4G-4G, 4G-3G, 4G-2G call MOS at cell edge, vs RSRQ, continuous call.

terms of signal strength, quality, and multipath contribution), having verified the strength of AMR CoDecs against these and having observed the working point where the radiolink failures occurred, we had finally all the information to set properly the thresholds for the VoLTE inter-RAT handovers to 3G or 2G (also called SRVCC - Single Radio Voice Call Continuity), in order to maintain the 4G VoLTE terminal as long as possible over LTE (to benefit for the higher data rate achievable in 4G) before handing-over it to 3G or 2G, to grant voice continuity and avoid a call dropped. Thanks to this campaign, finally we chose to set the thresholds for the inter-RAT handover to 3G/2G to -120 dBm. As a result, the terminals are kept as much as possible over 4G and (only when they have a VoLTE call ongoing) are finally moved to the other RATs. The VoLTE call completion rate in Telecom Italia's network, thanks to this setup, is almost 99.9%.

7 Conclusions

When running VoLTE calls, the MOS is firstly influenced by the selected CoDec rather than the radio conditions. The higher the coding bitrate, the better the quality perceived by the user. Due to very poor radio conditions, this is maintained until the call is finally dropped. It is presented a methodology based on FFT to reproduce the signal fluctuations which are typical for indoor and outdoor environments (please see [23, 24]) in an RC, where one or two UE are placed. The aim is to analyze the MOS when the radio conditions degrade and become very poor. Results allow to understand what are the best thresholds to trigger VoLTE inter system handover to UMTS or GSM, respecting both requirements to maintain the user over the LTE network as much as possible - to benefit for higher data bitrates - without the risk of dropping the voice call. This has been performed by continuous voice calls between 4G-4G users, 4G-3G users and 4G-2G users, observing the RSRP, RSRQ and DL SINR values until the call was finally dropped. Test results exhibit that no valid measures of MOS for RSRP values lower than -126 dBm and for RSRQ values lower than -23 dB are present. As a consequence, the threshold values for SRVCC to hand over to UMTS and GSM have to be set by the operator to values higher than these ones. Finally, the concepts of the performed tests are also valid in the outlook of the 5G.

8 References

- ITU-T P. 800: Methods for subjective determination of transmission quality ITU-T study group 12, 1993-1996
- ITU-T P.862.3: Methods for objective and subjective assessment of quality., 2006-2011
- Hill, D.A.: 'Plane wave integral representation for fields in reverberation chambers', *IEEE Trans Electromagn Compat*, 1998, **40**, (3), pp. 209-217
- Corona, P., Ferrara, G., Migliaccio, M.: 'Reverberating chambers as sources of stochastic electromagnetic fields', *IEEE Trans Electromagn Compat*, 1996, **38**, (3), pp. 348-356

- 5 Serra, R., Marvin, A.C., Moglie, F., Mariani Primiani, V., Cozza, A., Arnaut, L.R., et al.: 'Reverberation chambers a la carte: An overview of the different mode-stirring techniques', *IEEE Electromagn Compat*, 2017, **6**, (1), pp. 63–78
- 6 Moglie, F., Gradoni, G., Bastianelli, L., Mariani Primiani, V.: 'A mechanical mode-stirred reverberation chamber inspired by chaotic cavities'. In: *Metrology for Aerospace (MetroAeroSpace)*, 2015 IEEE. Benevento, Italy, 2015. pp. 437–441
- 7 Arnaut, L., Holloway, C., Kildal, P.S., Mariani Primiani, V.: 'Guest editorial of special issue on recent developments on the use of reverberation chambers for testing wireless systems', *IET Science, Measurement Technology*, 2015, **9**, (5), pp. 533–534
- 8 Chen, X., Tang, J., Li, T., Zhu, S., Ren, Y., Zhang, Z., et al.: 'Reverberation chambers for over-the-air tests: An overview of two decades of research', *IEEE Access*, 2018, **6**, pp. 49129–49143
- 9 Bastianelli, L., Gradoni, G., Micheli, D., Barazzetta, M., Diamanti, R., Moglie, F., et al.: 'Reverberation chambers for testing LTE wireless communication systems'. In: *Proc. Int. Conf. Electromagn. Adv. Applic. (ICEAA)*. Verona, Italy, 2017. pp. 722–725
- 10 Kildal, P., Chen, X., Orlenius, C., Franzen, M., Patané, C.S.L.: 'Characterization of reverberation chambers for OTA measurements of wireless devices: Physical formulations of channel matrix and new uncertainty formula', *IEEE Trans Antennas Propag*, 2012, **60**, (8), pp. 3875–3891
- 11 Patané, C.S.L., Skårbratt, A., Rehammar, R., Orlenius, C.: 'Basic and advanced MIMO OTA testing of wireless devices using reverberation chamber'. In: *Proc. 8th Eur. Conf. Antennas Propag.*, The Hague, Netherlands, 2014. pp. 3488–3492
- 12 Micheli, D., Barazzetta, M., Diamanti, R., Obino, P., Lattanzi, R., Bastianelli, L., et al.: 'Over-the-air tests of high-speed moving lte users in a reverberation chamber', *IEEE Trans Veh Technol*, 2018, **67**, (5), pp. 4340–4349
- 13 Barazzetta, M., Micheli, D., Diamanti, R., Bastianelli, L., Moglie, F., Mariani Primiani, V.: 'Optimization of 4G wireless access network features by using reverberation chambers: Application to high-speed train LTE users'. In: *46th European Microwave Conference (EuMC)*. London, United Kingdom, 2016. pp. 719–722
- 14 Genender, E., Holloway, C.L., Remley, K.A., Ladbury, J.M., Koepke, G., Garbe, H.: 'Simulating the multipath channel with a reverberation chamber: Application to bit error rate measurements', *IEEE Trans Electromagn Compat*, 2010, **52**, (4), pp. 766–777
- 15 Bastianelli, L., Giacometti, L., Mariani Primiani, V., Moglie, F.: 'Effect of absorber number and positioning on the power delay profile of a reverberation chamber'. In: *2015 IEEE International Symposium on Electromagnetic Compatibility (EMC)*. (Dresden, Germany), 2015. pp. 422–427
- 16 Patané, C.S.L., Skårbratt, A., Rehammar, R., Orlenius, C.: 'On the use of reverberation chambers for assessment of MIMO OTA performance of wireless devices'. In: *7th European Conference on Antennas and Propagation (EuCAP)*. Gothenburg, Sweden, 2013. pp. 101–105
- 17 Park, S.J., Jeong, M.H., Bae, K.B., Kim, D.C., Minz, L., Park, S.O.: 'Performance comparison of 2x2 MIMO antenna arrays with different configurations and polarizations in reverberation chamber at millimeter-waveband', *IEEE Trans Antennas Propag*, 2017, **65**, pp. 6669–6678
- 18 Genender, E., Holloway, C.L., Remley, K.A., Ladbury, J., Koepke, G., Garbe, H.: 'Use of reverberation chamber to simulate the power delay profile of a wireless environment'. In: *Proc. IEEE Int. Symp. Electromagn. Compat.* Hamburg, Germany, 2008. pp. 1–6
- 19 Lemoine, C., Amador, E., Besnier, P.: 'On the K-factor estimation for rician channel simulated in reverberation chamber', *IEEE Trans Antennas Propag*, 2011, **59**, (3), pp. 1003–1012
- 20 3GPP TS 34.114: User equipment UE/mobile station MS over the air OTA antenna performance, conformance testing – release 11, v. 11.3.0, 2012
- 21 3GPP 3G TR 26.975: Technical specification group TSG-SA4: Codec; performance characterization of the AMR speech coded, v. 1.1.0, 1999
- 22 Hussain, A., Kildal, P.S.: 'Study of OTA throughput of lte terminals for different system bandwidths and coherence bandwidths'. In: *7th European Conference on Antennas and Propagation (EuCAP)*. Gothenburg, Sweden, 2013. pp. 312–314
- 23 'Guidelines for evaluation of radio interface technologies for imtdvanced, international telecommunication union', Geneva, Switzerland, 2009
- 24 ITU Report M.2135-1: Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz
- 25 Micheli, D., Barazzetta, M., Moglie, F., Mariani Primiani, V.: 'Power boosting and compensation during OTA testing of a real 4G LTE base station in reverberation chamber', *IEEE Trans Electromagn Compat*, 2015, **57**, (4), pp. 623–634
- 26 Barazzetta, M., Micheli, D., Bastianelli, L., Diamanti, R., Totta, M., Obino, P., et al.: 'A comparison between different reception diversity schemes of a 4G-LTE base station in reverberation chamber: a deployment in a live cellular network', *IEEE Trans Electromagn Compat*, 2017, **59**, (6), pp. 2029–2037
- 27 Micheli, D., Barazzetta, M., Carlini, C., Diamanti, R., Mariani Primiani, V., Moglie, F.: 'Testing of the carrier aggregation mode for a live LTE base station in reverberation chamber', *IEEE Trans Veh Technol*, 2017, **66**, (4), pp. 3024–3033
- 28 Guidelines for evaluation of radio interface technologies for IMT-Advanced, International Telecommunication Union - ITU Report, M.2135-1, Dec. 2009
- 29 Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz, International Telecommunication Union - ITU Recommendation P.1238-7, Feb. 2012.