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18SIP02 5GRFEX D3

Evaluation report describing how the stringent RF-EMF limits affect the 5G wireless communication performance

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List of Abbreviations

3GPP	3rd Generation Partnership Project
3G	3rd Generation Wireless Systems
4G	4th Generation Wireless Systems
5G	5th Generation Wireless Systems
BER	Bit Error Rate
BLER	Block Error Rate
COST	European Cooperation in Science and Technology
CTIA	Cellular and Telecommunication Industry Association
CW	Continuous Wave
EMF	Electromagnetic Field
EU	European Union
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input-Multiple-Output transmission
mMIMO	Massive Multiple-Input-Multiple-Output
NR	New Radio
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RE	Resource Element
RF	Radio Frequency
Rx	Receiving End
SI	International System of Units
SNR	Signal-to-Noise
SSB	Synchronisation Signal Block
Tx	Transmitting End
UE	User Equipment
ZF	Zero Forcing

1 Scope of the document

This document, namely, Deliverable 3 (D3), serves as an evaluation report on work carried out under work package 2 (WP2) of the European Association of National Measurement Institutes (EURAMET) funded support for impact (SIP) project – 18SIP02, entitled “Metrology for RF exposure from Massive MIMO 5G base station: Impact on 5G network deployment (5GRFEX)”. This evaluation report presents the evaluation of how stringent radio frequency electromagnetic field (RF-EMF) limits affect the fifth generation (5G) wireless communication performance. A measurement campaign has been carried out using a developed user-controllable massive multiple-input-multiple-output (mMIMO) beamforming system, Surrey user equipment (UE), and traceable RF-EMF measurement systems. In this evaluation report, the focus is given to the study of how the communication link performance between mMIMO base station (BS) and UE(s) are affected by the variation of the mMIMO BS transmitting end (Tx) power, number of UEs, and UE’s modulation and coding scheme (MCS). Based on experimental evidence, measurement results are analysed to enable the insight understanding, and the relevant conclusions are drawn regarding the evaluation on how stringent RF-EMF limits affect the 5G wireless communication performance.

2 Introduction

The digital economy is essential for wealth creation. The demand for high-speed communication for a range of diverse applications has driven the global digital agenda to better exploit the 5G new radio (NR) wireless technologies for fostering innovation and economic growth. 5G is currently being rolled out in a number of countries. In Europe, the limitation of electromagnetic field (EMF) exposure is regulated on the basis of the 1998 guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1]. Within the European Union (EU) legal framework, these guidelines are enshrined in Council Recommendation 1999/519/EC of 12 July 1999 [2] for general public and Directive 2013/35/EU of 26 June 2013 [59] for workers. However, public concern over potential health risks from RF-EMF exposure from 5G NR BSs has led to stringent RF exposure compliance regulation in some countries, which goes beyond the guidelines set out by the ICNIRP. Recently, ICNIRP has issued its latest guidelines for 5G in 2020 [3], [4].

This restrictive regulation will affect the coverage and quality of the service provided to the consumers and has already had impact on fourth generation (4G) networks [5] and is envisaged to be problematic for the design and deployment of effective 5G networks [4], [6]–[8] – meaning that 5G communication systems may not work in some geographical areas and that the seamless connectivity promised by 5G may not be possible. Furthermore, when it comes to 5G BS deployment, operators are facing un-harmonised RF-EMF regulatory challenges in certain countries, regions and even cities. For example, in a number of European Member States, e.g. Switzerland and Italy, a different regulation is put in place where the current RF-EMF exposure limits are 4 V/m and 6 V/m, respectively, which is much stricter than the ICNIRP guidelines at 61 V/m [9]. Regulators, operators, 5G BS manufacturers, and equipment suppliers all require reliable and agreed assessment of RF-EMF exposure levels to support consistent and effective 5G regulation and network design.

The conventional RF-EMF exposure measurement methods for defining the BS exclusion zone (a compliance boundary around the BS with no access to general public) in both the third generation (3G) and fourth generation (4G) networks are based on the use of the maximum worst case exposure in every possible direction for a defined time-period. These methods make it problematic for operators to deploy 5G mMIMO BSs on sites with pre-existing 3G and 4G BSs and are becoming obsolete to quantify the RF-EMF exposure of 5G BSs employing complex beamforming technology such as mMIMO, which allow energy to be focused in sharp high-gain beams in the direction of a specific mobile user. Furthermore, different contributions have demonstrated that these methods are not suitable for 5G BSs [8], [9], which resulting in non-realistically large exclusion zone areas. Especially, in practice, it is envisaged that 5G mMIMO BSs do not emit at full power all the time in every direction whereby when multiple mobile users are served by a mMIMO BS, the emitted power is split between different directions.

Therefore, there is a need to develop new reliable and robust methods for assessing the RF-EMF exposure levels of 5G for supporting consistent and effective 5G regulation and network design; methods based on rigorous scientific evidence to ensure a good balance between user experience and public safety, e.g. ensuring that high power user service beams are only transmitted on a need-to basis [5], [10]. This evaluation report extends our preliminary work in D1 and D2 into investigating how the stringent RF-EMF limits affect the 5G wireless communication performance. A measurement campaign based on traceable experimental-based RF-EMF exposure and link performance evidence within a real-world indoor environment has been carried out using the developed user-controllable mMIMO beamforming system, Surrey user equipment (UE), and traceable RF-EMF measurement systems. Focus is given on the study of how the communication link performance between mMIMO BS and UE(s) are affected by the variation of the mMIMO BS Tx power, number of UEs, and UE 's MCS. Note that, with user programmable capability and specific knowledge on beam pattern, the Surrey mMIMO enables the project team to gain understanding into the relevant insight considering these varying factors. Based on the experimental evidence, the measurement results are analysed to enable the insight and understanding, and the relevant conclusions are drawn regarding the evaluation on how the stringent RF-EMF limits affect the 5G wireless communication performance.

3 Measurement Campaign

3.1 Hardware and measurement setup

In the measurement campaign, the developed traceable RF-EMF measurement capabilities as detailed in Section 2.2 of the D1 report have been employed, which consists of:

- a user-controllable Surrey mMIMO beamforming Tx system [11] with up to 128 channels transmit antenna array
- Up to 5 UEs with Surrey 4-dipole-element receive antenna array each connected to a MegaBEE receiver
- An RF-EMF measurement system that consists of a handheld Keysight FieldFox N9917B portable spectrum analyser [12] and an AGOS ARIA-6000 triaxial isotropic field probe [13]

Note that the Surrey 4-dipole-element receiving systems were used as RF-EMF measurement system in the D1 report whereby in this report, during the measurement campaign, they were employed to operate as UEs. For this indoor measurement campaign, all the measurements were performed inside an indoor environment within a large meeting room, located in the basement of the 5G Innovation Centre (5GIC) at the University of Surrey. The room is 15 m long, 7.5 m wide, and 3 m high. Typical furniture, such as chairs and desk within the room were placed aside during the measurements. The room is surrounded by glass, brick and plasterboard walls. The floor is made of concrete and carpeted. The concrete suspended ceiling was equipped with some hanging lighting and projector equipment. During the measurement, all the measurement instruments were located inside the room. Figure 1 shows an illustrative measurement setup of Surrey mMIMO Tx array with several MegaBEE UE receivers located at different distances and angles from the mMIMO system within the indoor environment. The measurements are performed within an 8 m × 6 m area, which is divided into a grid of 48 square by 1 m for the ease of measurement, as depicted in Figure 1.

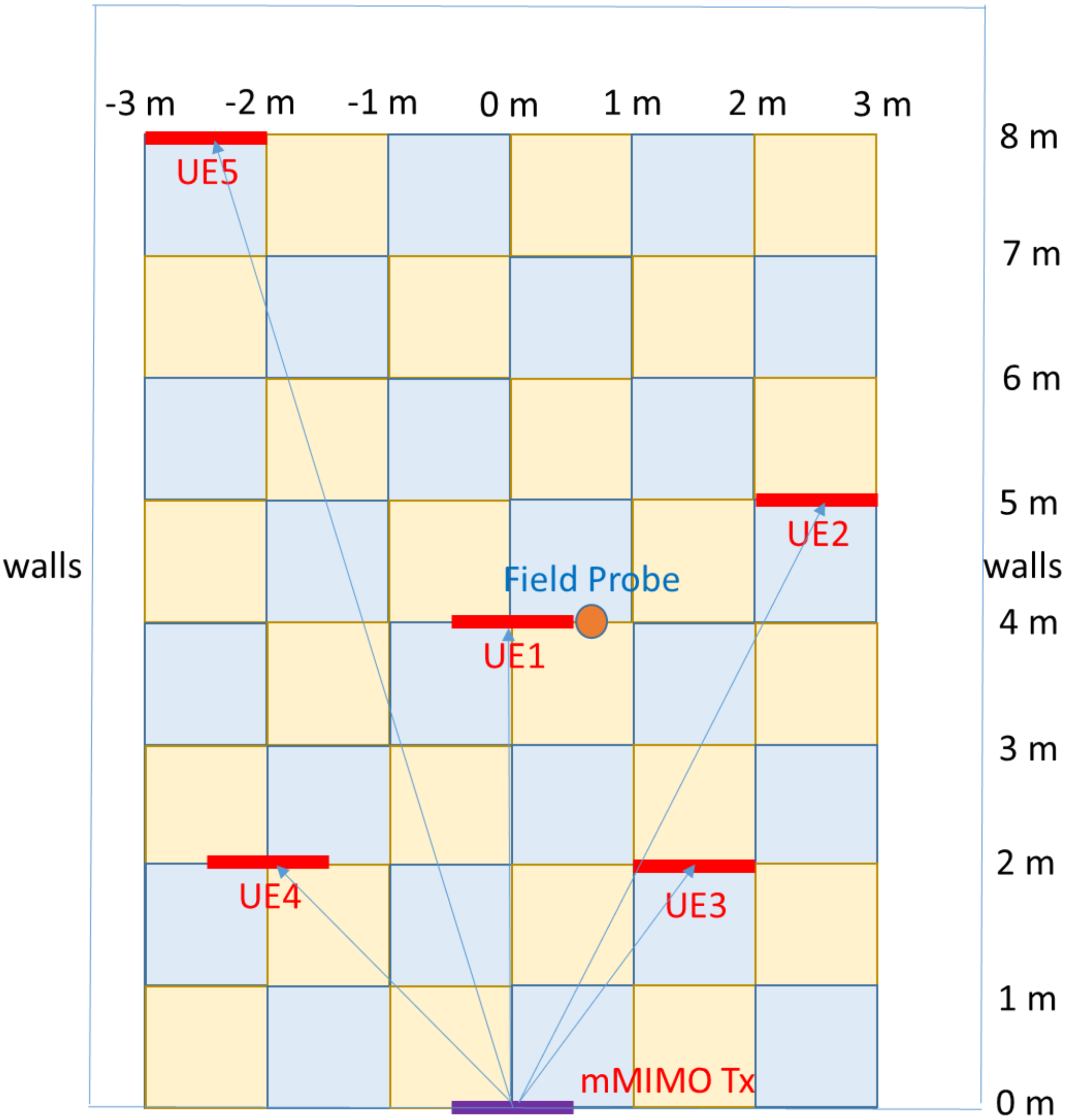


Figure 1 *Measurement setup for 96 active mMIMO Tx at (0 m, 0 m), the five UEs and the RF-EMF probe.*

The mMIMO Tx system was programmed to perform downlink zero forcing (ZF) precoding after channel state information (CSI) acquisition for different beamforming scenarios with respect to the associated user terminal antenna setups and positions. Using a calibrated triaxial isotropic field-probe as part of the Keysight RF-EMF measurement system, the received channel power for each beamforming scenario was acquired and then converted into the correspondent RF-EMF. The following shows the relevant MIMO downlink configuration setting employed in this measurement campaign:

- RF operating frequency centric at 2.63 GHz
- 40 MHz instantaneous data bandwidth per channel
- OFDM frames with subcarrier spacing of 15 kHz in TDD mode
- Transmission rate at 61.44 MSps for a fixed length of 65536 samples (i.e. 2^{16})
- Keysight RF-EMF measurement system (Spectrum analyser and triaxial isotropic field-probe)
- MATLAB baseband processing and zero-forcing beamforming
- Varying number of active mMIMO Tx with real-time transmission (i.e. 96, 64, 32, and 16)
- Varying mMIMO Tx Power: $P_{Tx\_dB} - i$ dB, $i = \{0:2:16\}$
- Varying number of active UE (i.e. 4-dipole-element Rx antenna array each with a MegaBEE

receiver) for stimulating beam pointing direction/location

- Varying symbol modulation order: QPSK, 16-QAM and 64-QAM
- Varying modulation code rate: 1/2, 2/3 and 4/5

With fixed number of active Tx antennas, for each beamforming scenario considered (i.e. different number of active UE(s)), the same measurement procedure was followed:

(1) first a pilot frame is sent from the mMIMO Tx system to each receiving location, which acquires and feeds back its CSI via the SFP+ cable;
(2) the mMIMO Tx system then estimates the CSI and uses it to generate ZF precoded data frame;
(3) finally the mMIMO Tx system transmits these ZF precoded data frames in a continuous manner while the probe measures the RF-EMF with varying mMIMO Tx power, symbol modulation order and modulation code rate.

In order to ensure that the ZF precodes reasonably well, the uncoded block-error-rate (BLER) is calculated at each UE based on the first received data frame. In this measurement campaign, both BLER and RF-EMF are measured. Note that, during the measurement campaign, all UEs stayed within the room while being activated or deactivated via a PC connected remotely to an accessible network. The power level of the mMIMO Tx system is normalized for all the above measurements.

3.2 Test scenarios and findings

With 4G and 5G technologies, a symbol is referred to as a resource element (RE). The relevant modulation and coding scheme (MCS) defines the number of useful bits which can be carried by one RE. The MCS setting, along with the MCS table defined by standardization bodies [14], determines the modulation order and code rate applied to a physical channel transmission. Its setting depends on radio signal quality in a wireless link. Good link quality will enable operation of a higher modulation order and code rate allowing more useful bits to be transmitted with an RE whereas bad link quality results in lower modulation order and code rate allowing for less useful bits to be transmitted with an RE. i.e. MCS setting (both modulation order and code rate) depends on Block Error Rate (BLER) and in practice, could be changed by 5G BS based on the application of an appropriate link adaptation algorithm.

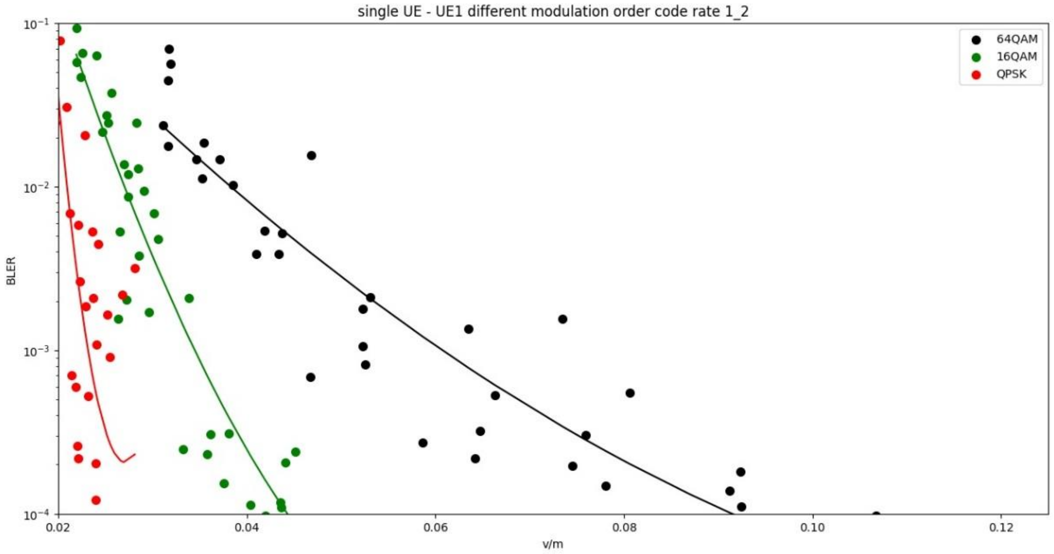
In this report, with a fixed number of active Tx antennas and UEs, the test scenarios considered include varying mMIMO Tx Power, symbol modulation order and modulation code rate. The relevant measured data are assessed by plotting the measured BLER versus RF-EMF plot for all varying factors. Note that Table 2 in D1 presents the BER values at each UE for each beamforming scenario shown in Figure 8 of D1; the results show that when using ZF precoding, the greater the number of users, the lower the quality of beamforming. But still in any case uncoded BER of around 10^{-3} can be achieved, which tends to confirm that the BS beam forms in the expected direction. The examples of the received constellation results for Quadrature Phase-Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (16-QAM) and 64-QAM are shown in Figure 10 of D1 report, which confirm the high link quality.

3.2.1 Number of active UEs

Considering combinations of different varying factors (i.e. mMIMO Tx power, modulation order, code rate) for a fixed number of active UEs, this section presents the measured ‘BLER versus RF-EMF’ plots for up to 5 UEs. The plots show under different scenarios (e.g. modulation order, code rate) how the increase of mMIMO Tx power (hence the measured RF-EMF) effects the resultant BLER where the same colour dot and link show, respectively, the actual measured values and the fitted line. During the measurement campaign, the mMIMO system was operated with 96 Tx antennas with Tx power level set to decrease from its default value down by 16 dB with a step of 2 dB between each decrement step. Five measurements were acquired at each step of the Tx power level. Note that the measurement of BLER is limited by noise floor vs. spectrum analyzer settings of Keysight Fieldfox.

3.2.1.1 One active UE

Figure 2 to Figure 6 show the 'BLER vs RF-EMF' plot for comparison between different modulation order under the same code rate with UE1, UE2, UE3, UE4 and UE5 activated, respectively.



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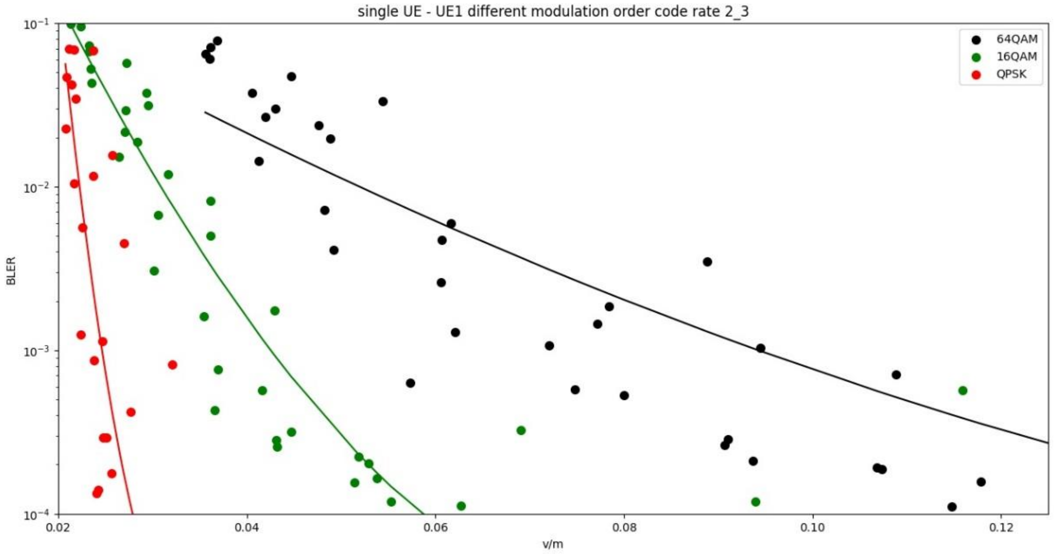

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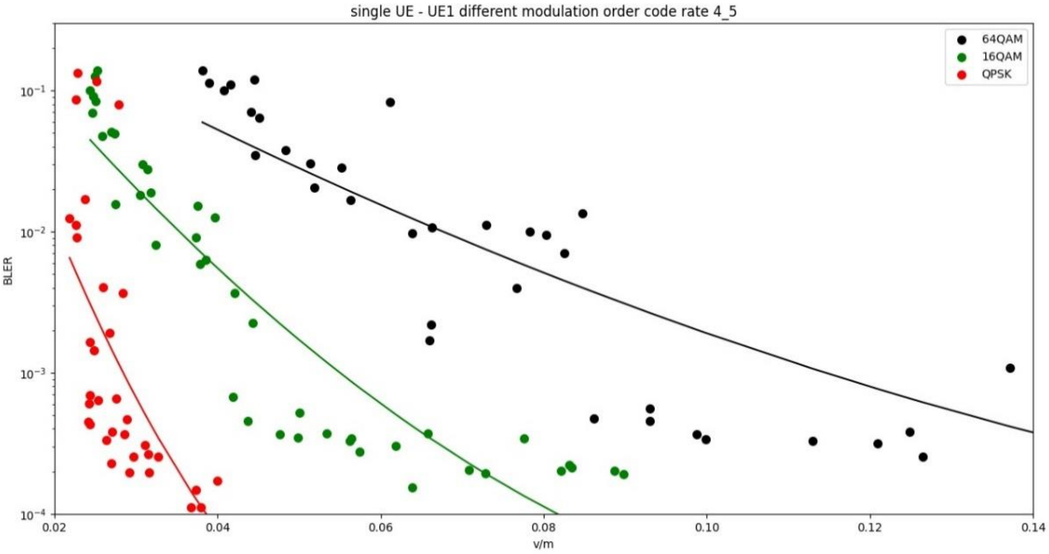
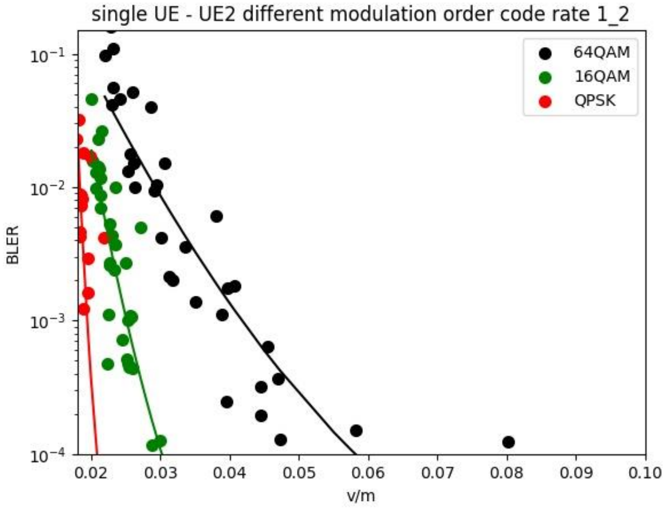


(c)

Figure 2 *BLER vs RF-EMF when UE1 is activated: Comparison between different modulation order for code rate of (a) 1/2; (b) 2/3; and (c) 4/5.*



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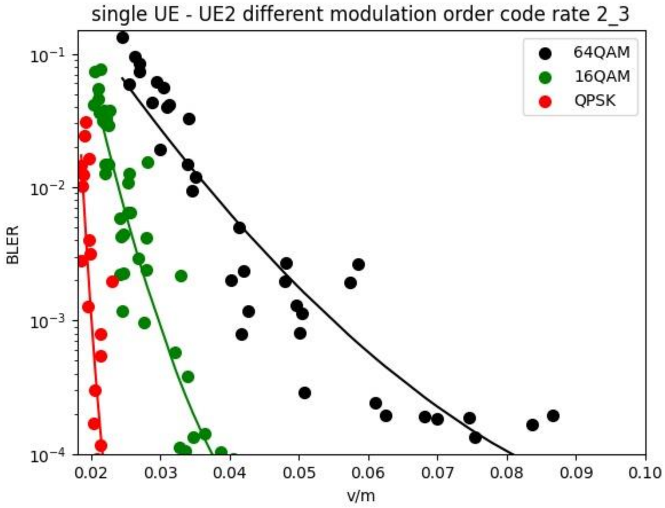

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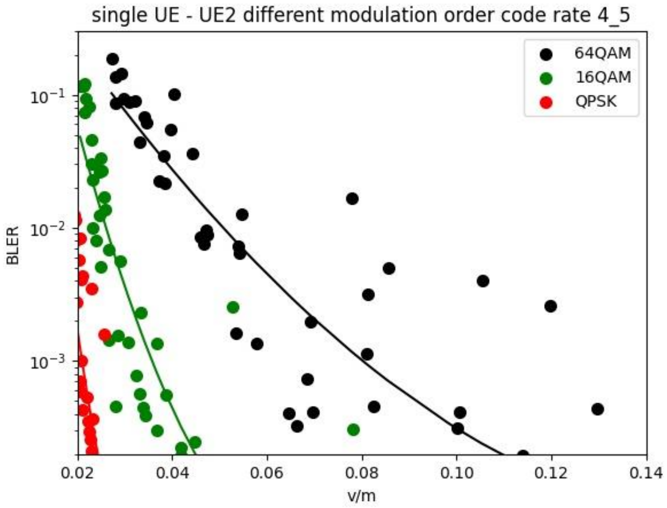
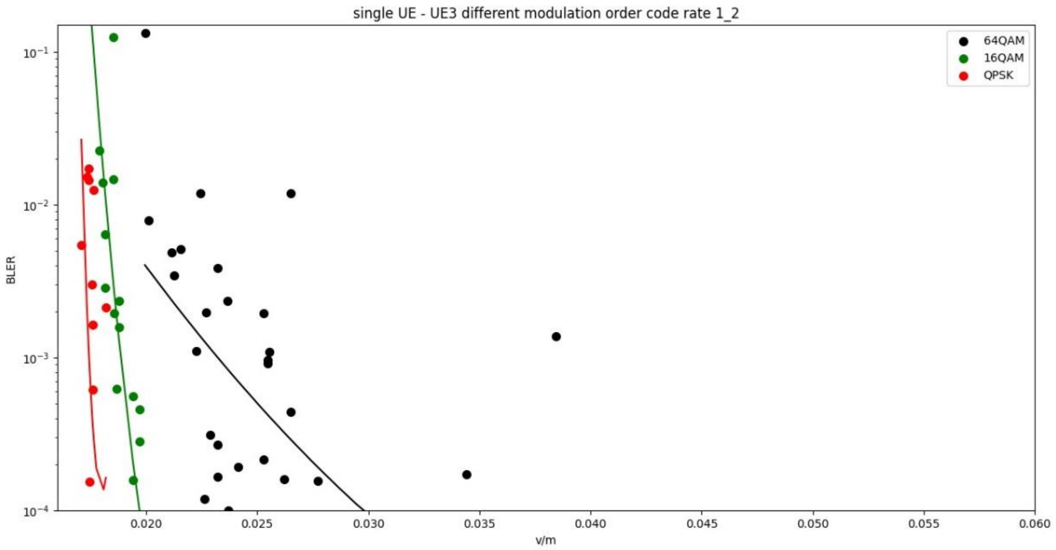


(c)

Figure 3 *BLER vs RF-EMF when UE2 is activated: Comparison between different modulation order for code rate of (a) 1/2; (b) 2/3; and (c) 4/5.*



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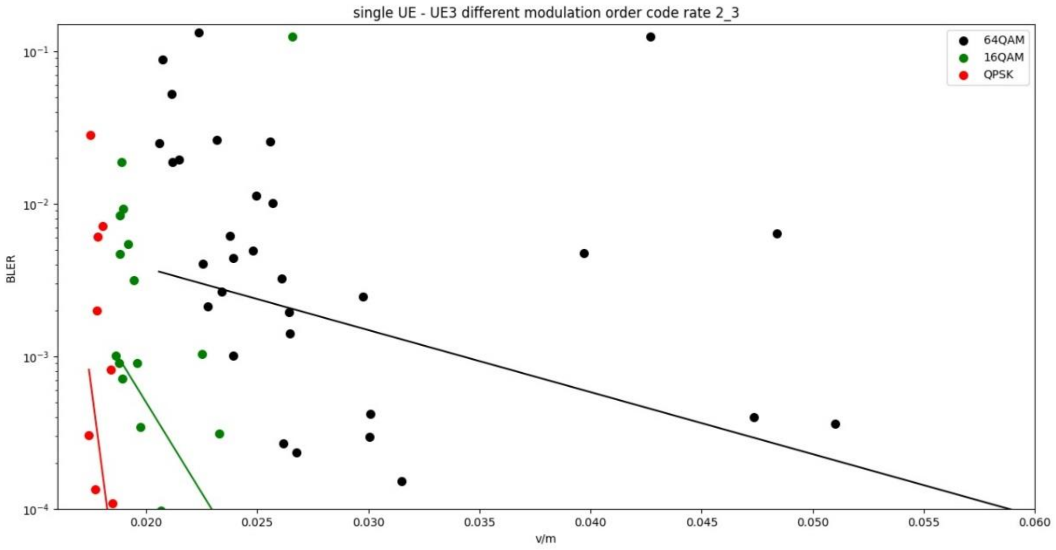

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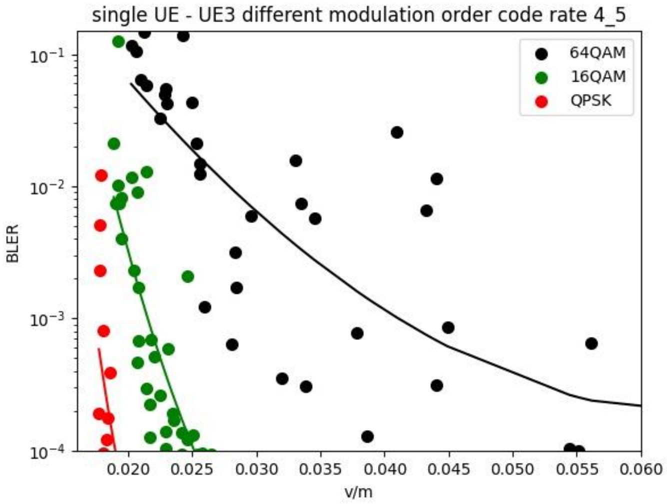
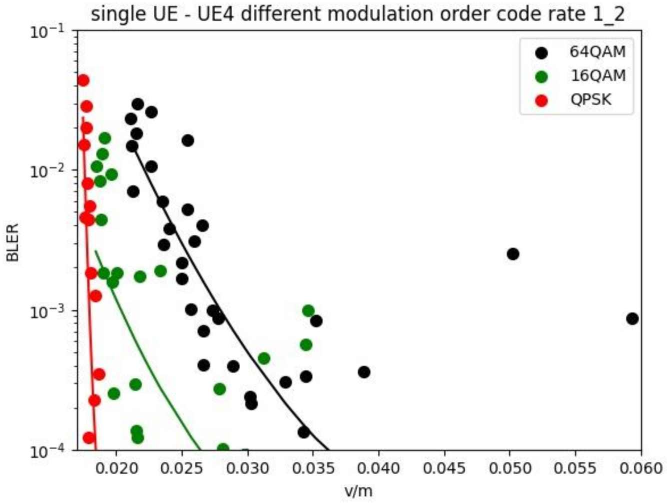


(c)

Figure 4 *BLER vs RF-EMF when UE3 is activated: Comparison between different modulation order for code rate of (a) 1/2; (b) 2/3; and (c) 4/5.*



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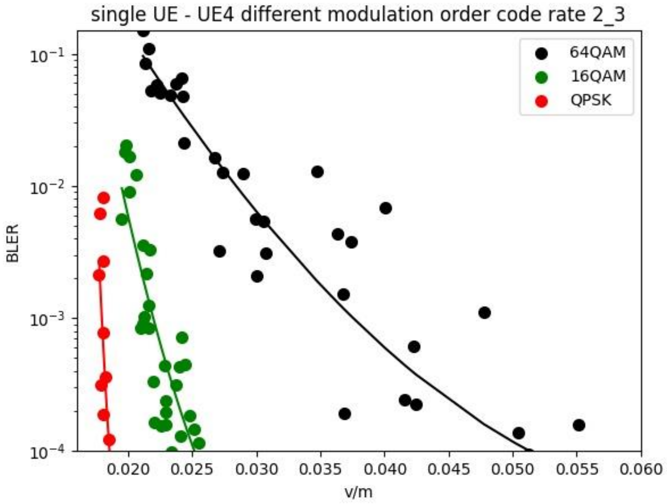

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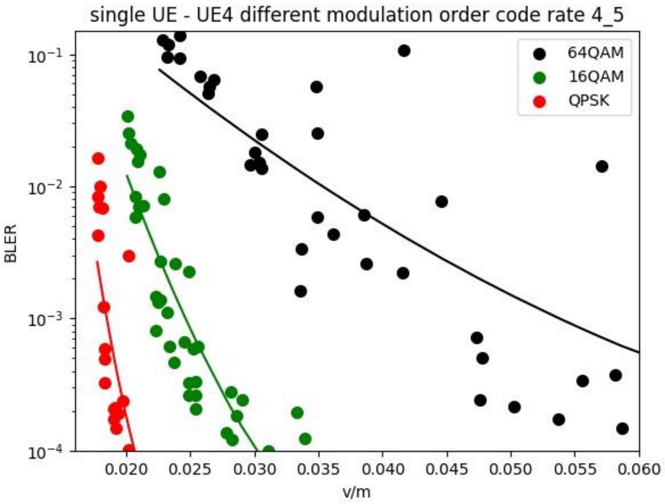
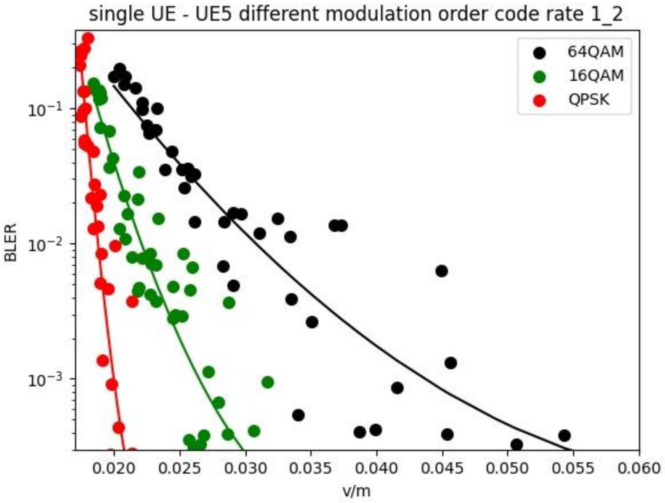


(c)

Figure 5 *BLER vs RF-EMF when UE4 is activated: Comparison between different modulation order for code rate of (a) 1/2; (b) 2/3; and (c) 4/5.*



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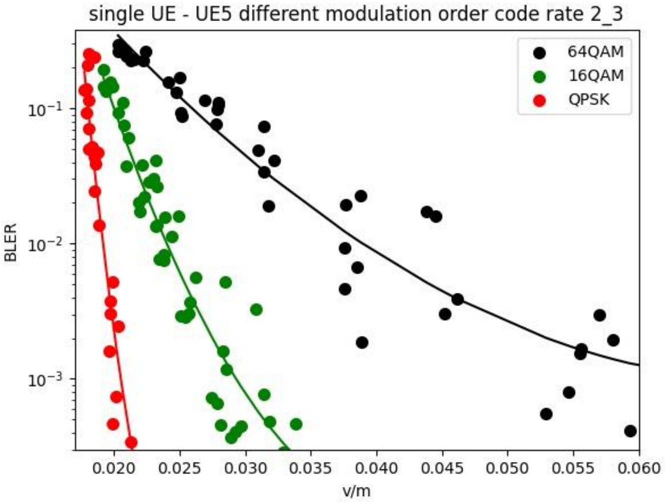

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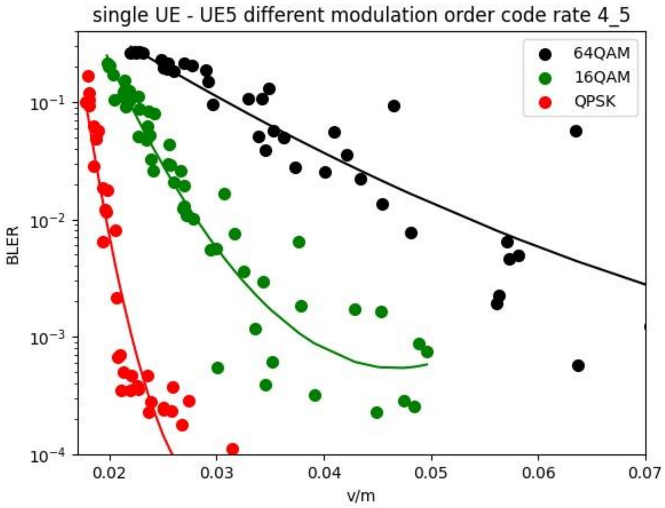


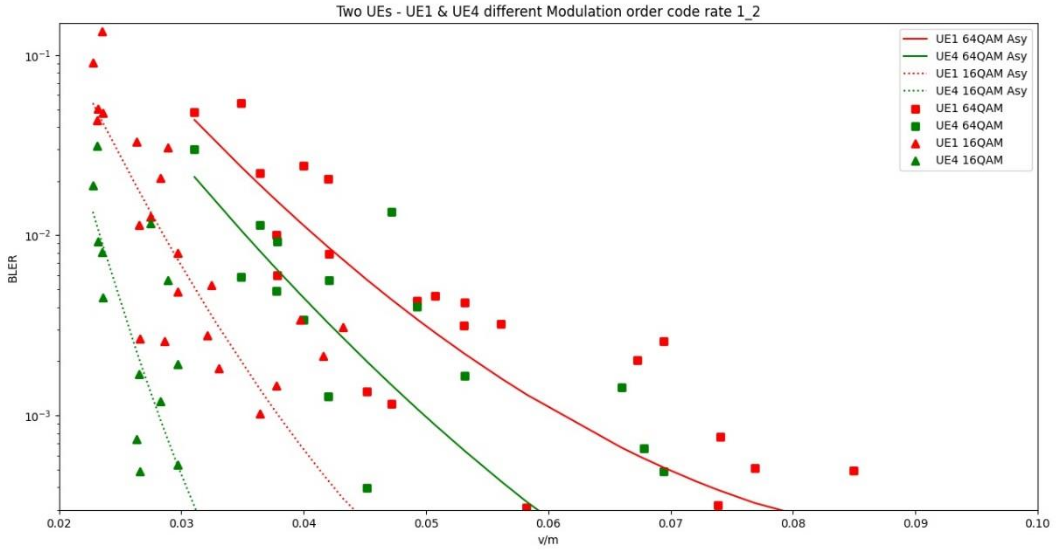
(c)

Figure 6 *BLER vs RF-EMF when UE5 is activated: Comparison between different modulation order for code rate of (a) 1/2; (b) 2/3; and (c) 4/5.*

From the above with a single active UE measured results, one observes generally that for the same RF-EMF level, BLER increases with higher code rate and modulation order whereby for a fixed BLER threshold, the RF-EMF also increases with higher code rate and modulation order.

3.2.1.2 Two active UEs

Figure 7 to **Error! Reference source not found.** show the 'BLER vs RF-EMF' plot for comparison between different modulation order under the same code rate with 'UE1 & UE4', 'UE2 & UE3', 'UE2 & UE5', and 'UE3 & UE4' activated, respectively.



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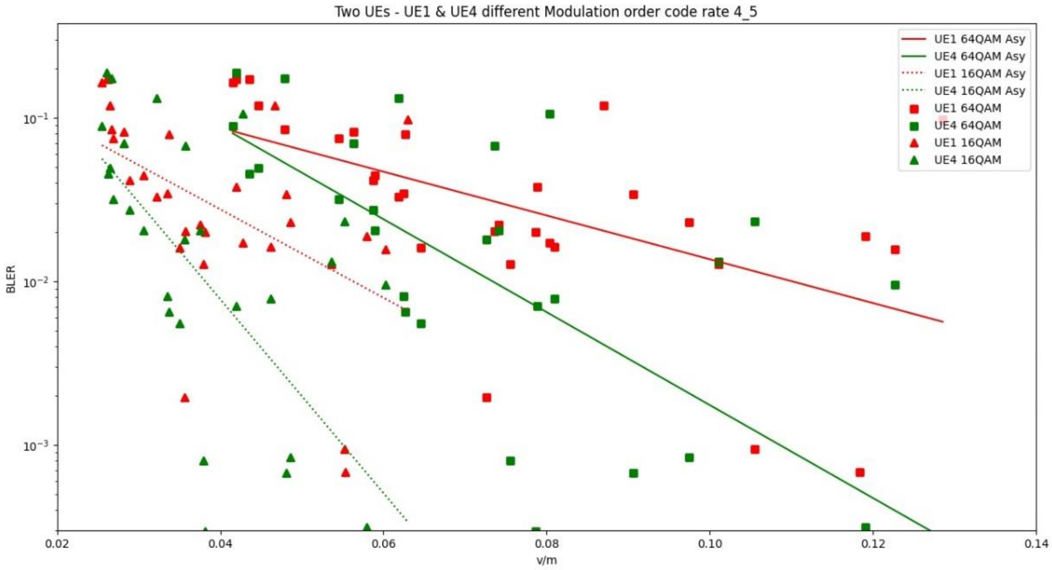

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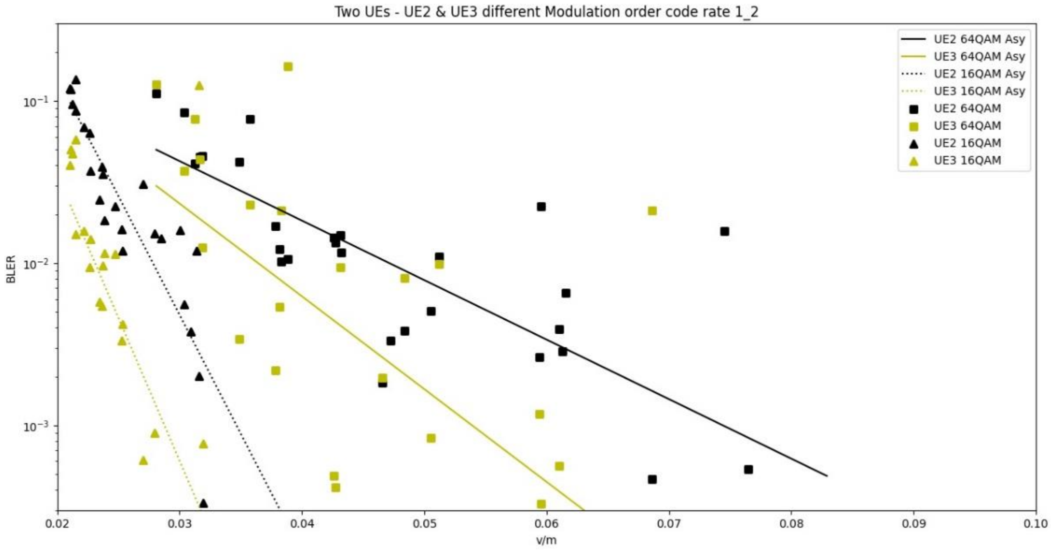
Figure 7 *BLER vs RF-EMF when UE1 and UE4 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*



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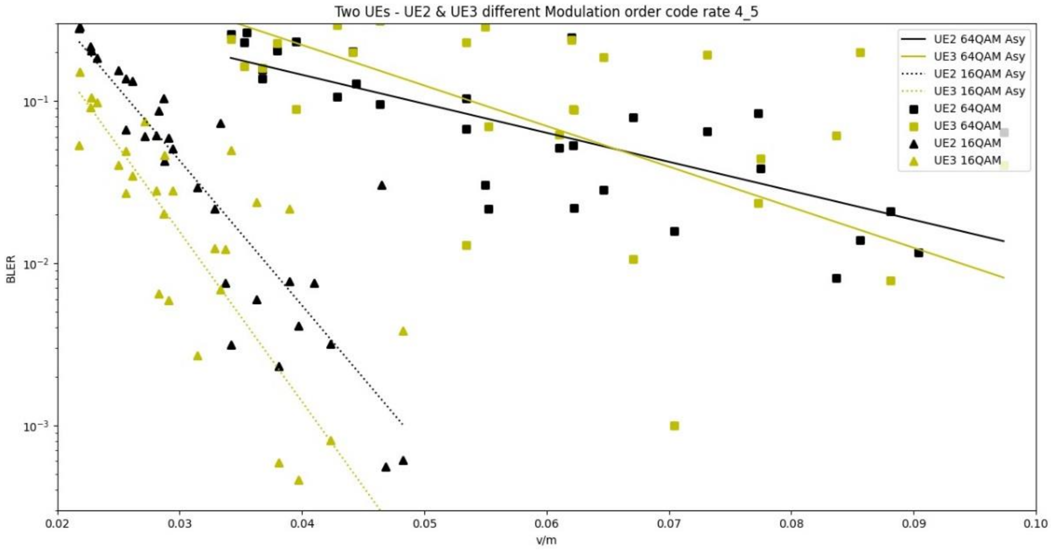

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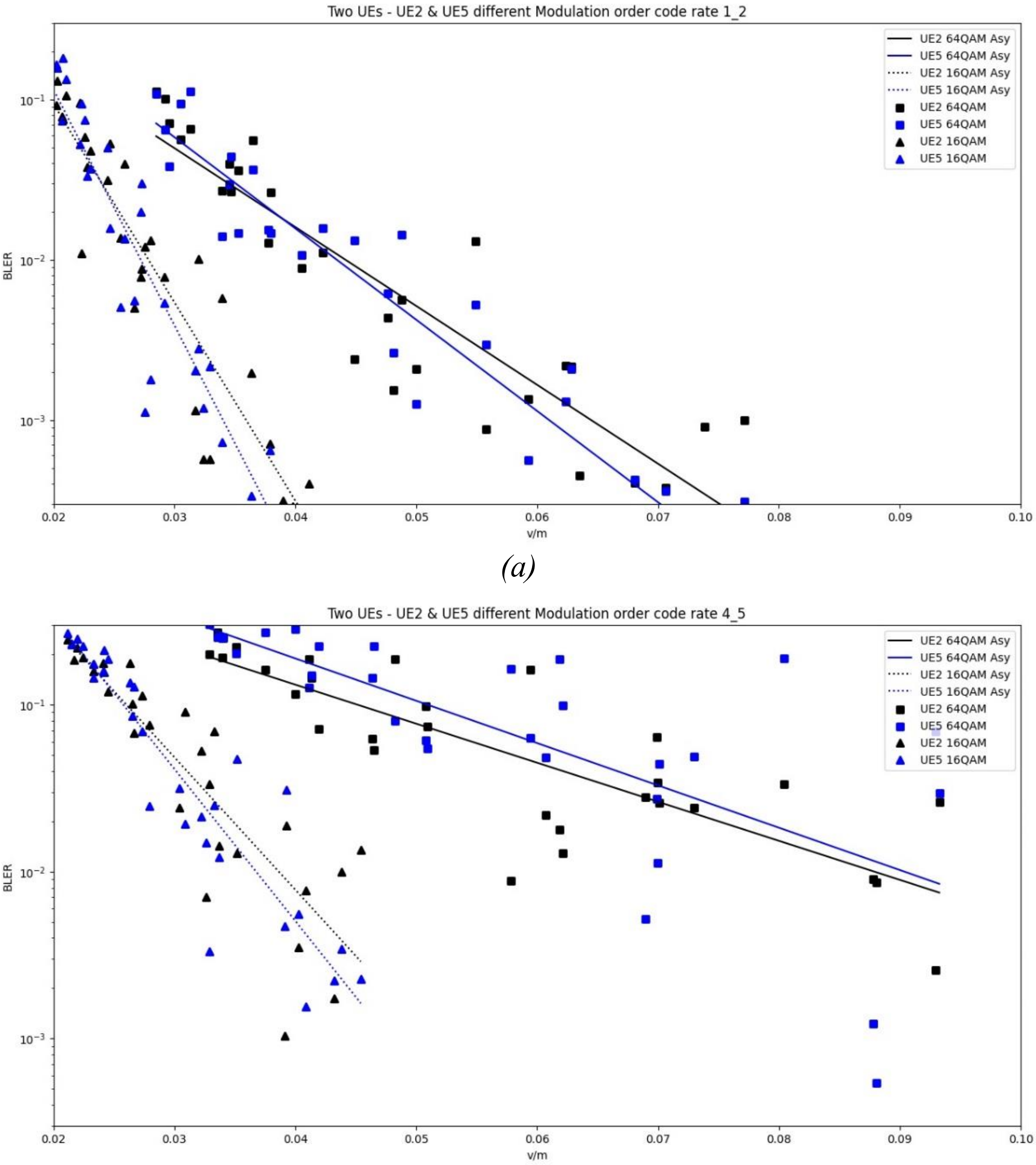
Figure 8 *BLER vs RF-EMF when UE2 and UE3 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*



(a)

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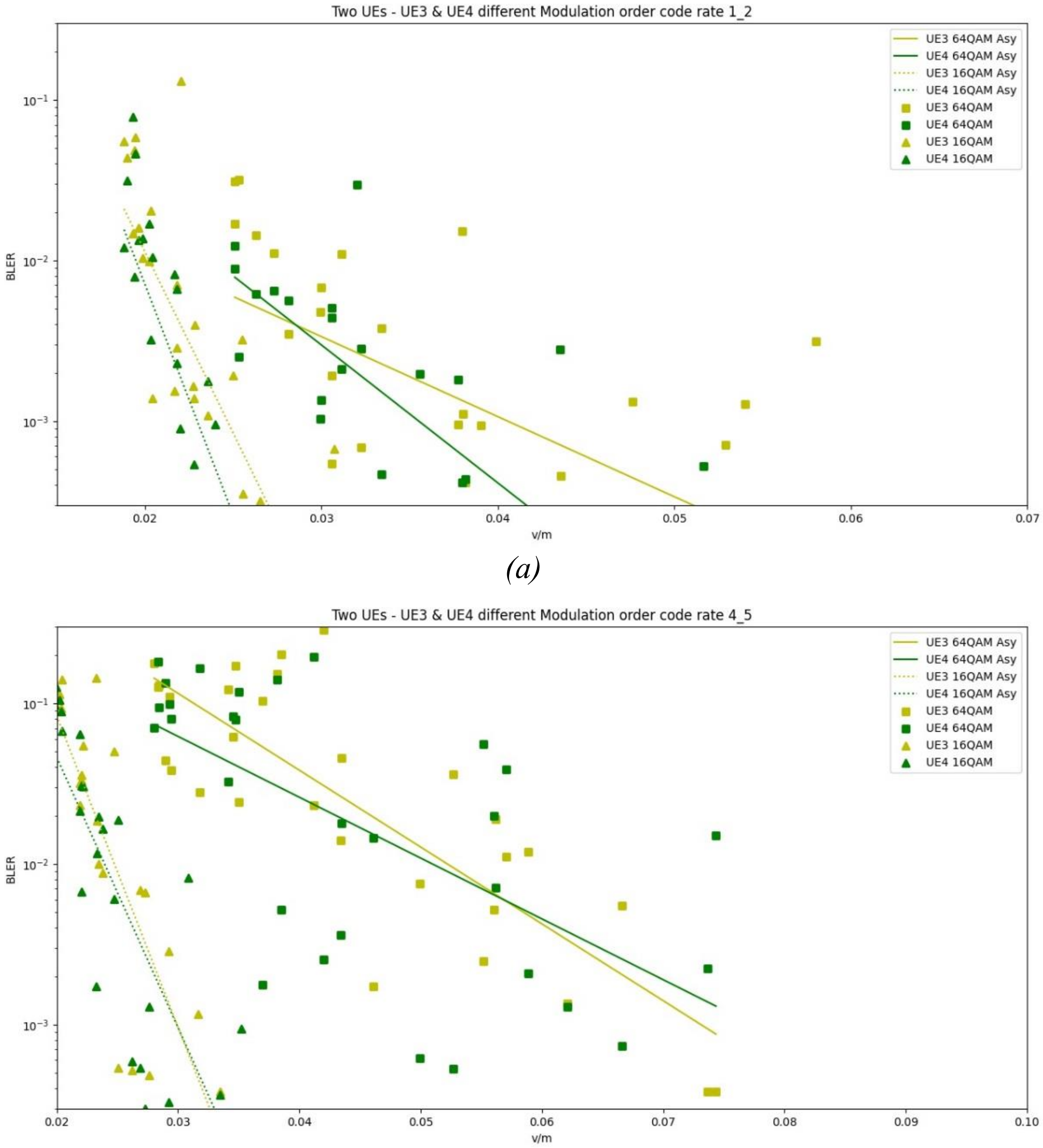
Figure 9 *BLER vs RF-EMF when UE2 and UE5 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*



(a)

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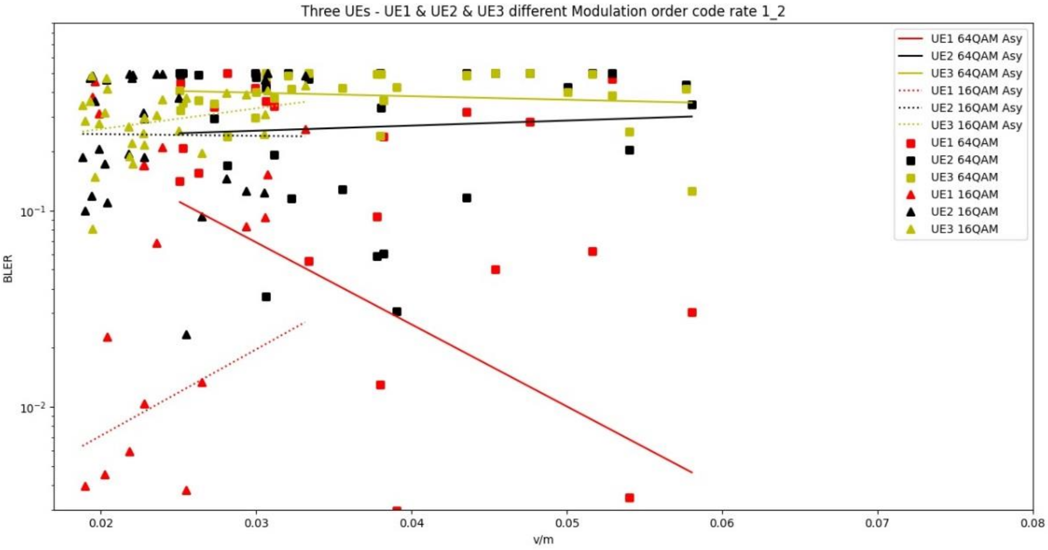
Figure 10 *BLER vs RF-EMF when UE3 and UE4 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*

From the above with two active UE measured results, similar observations are found as those obtained in one active UE measured results. i.e. generally, for the same RF-EMF level, BLER increases with higher code rate and modulation order whereby for a fixed BLER threshold, the RF-EMF also increases with higher code rate and modulation order.

3.2.1.3 Three active UEs

Figure 11 to Figure 13 show the ‘BLER vs RF-EMF’ plot for comparison between different modulation order under the same code rate with ‘UE1, UE2 & UE3’, ‘UE1, UE2 & UE5’, and ‘UE1, UE3 & UE4’ activated, respectively.



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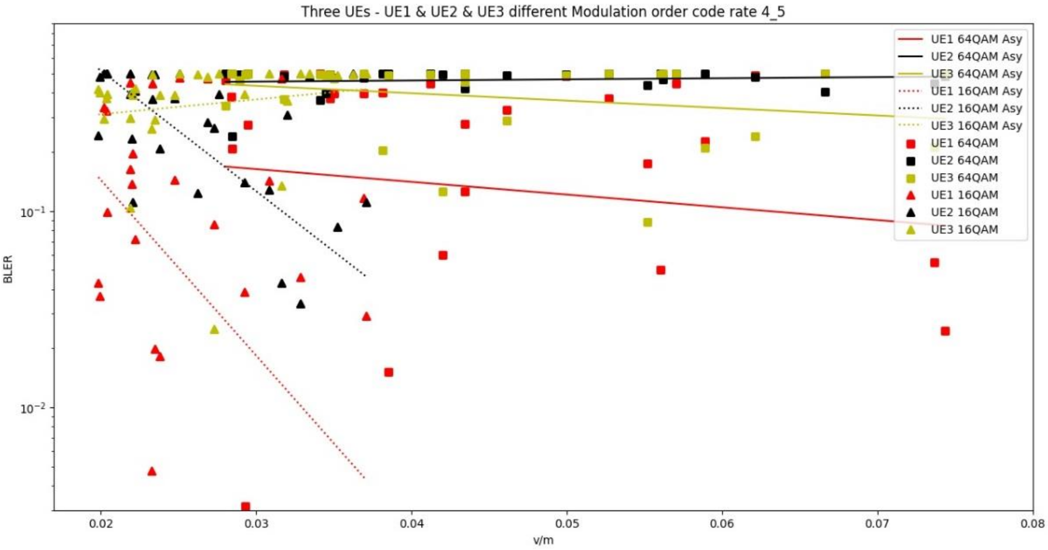

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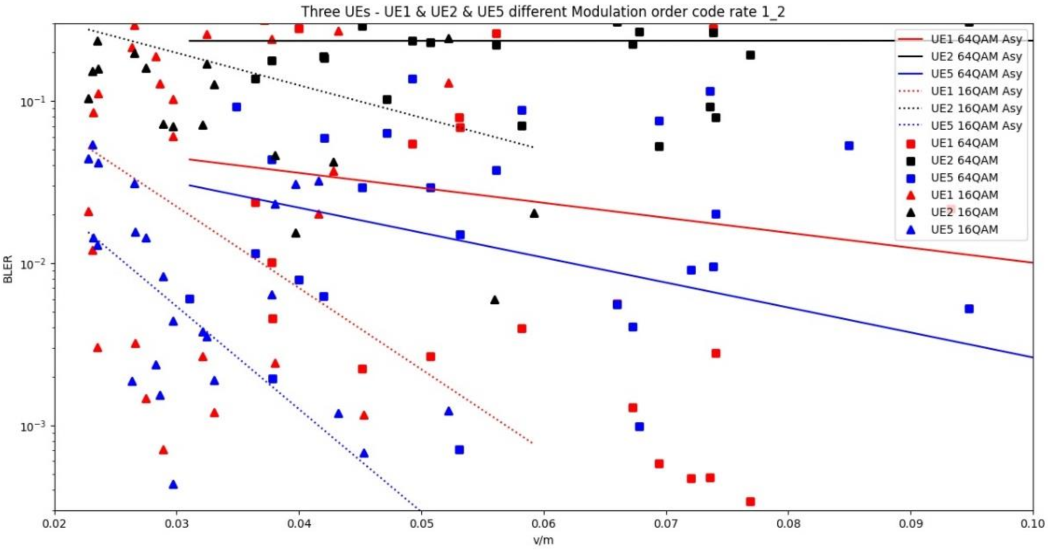
Figure 11 *BLER vs RF-EMF when UE1, UE2 and UE3 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*



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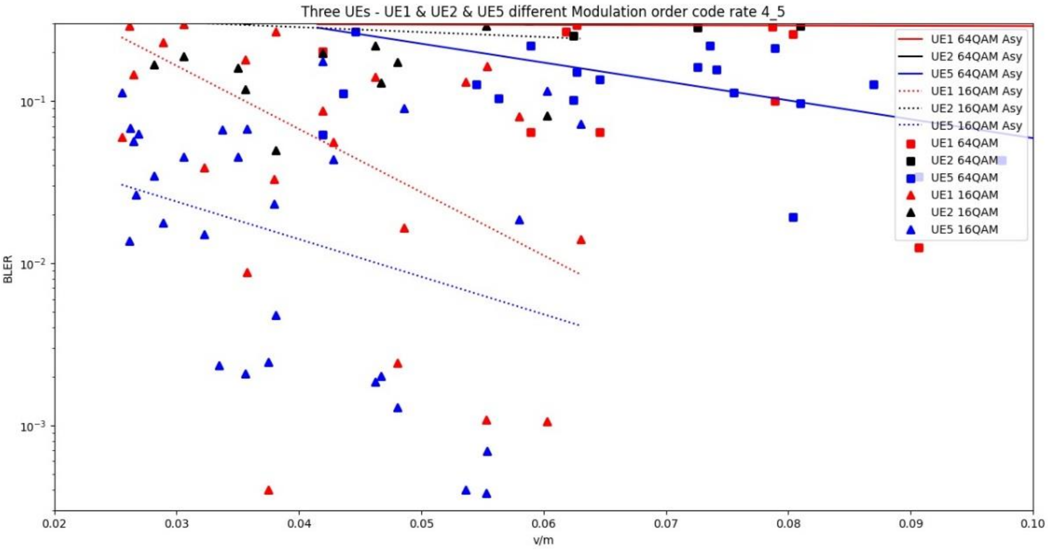

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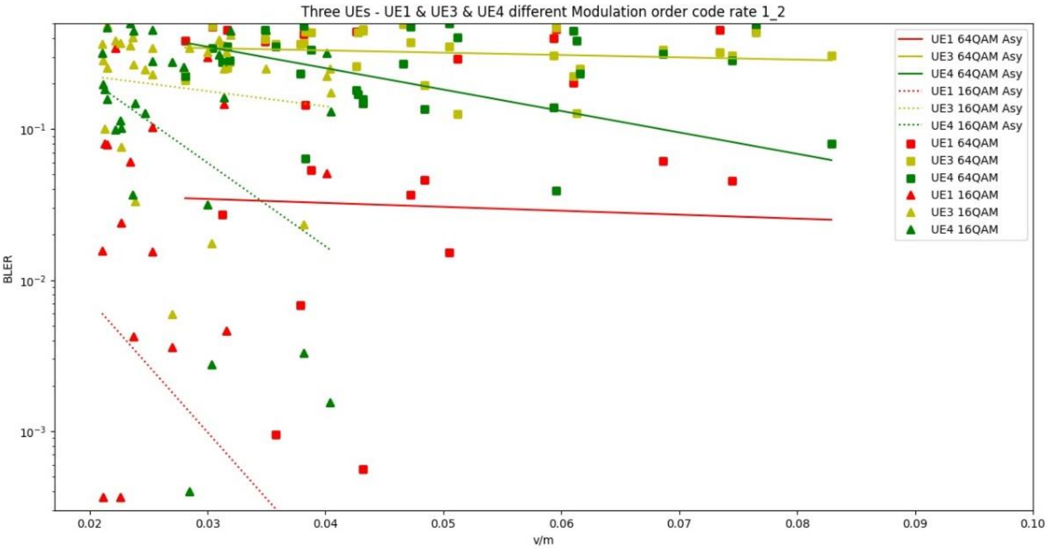
Figure 12 *BLER vs RF-EMF when UE1, UE2 and UE5 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*



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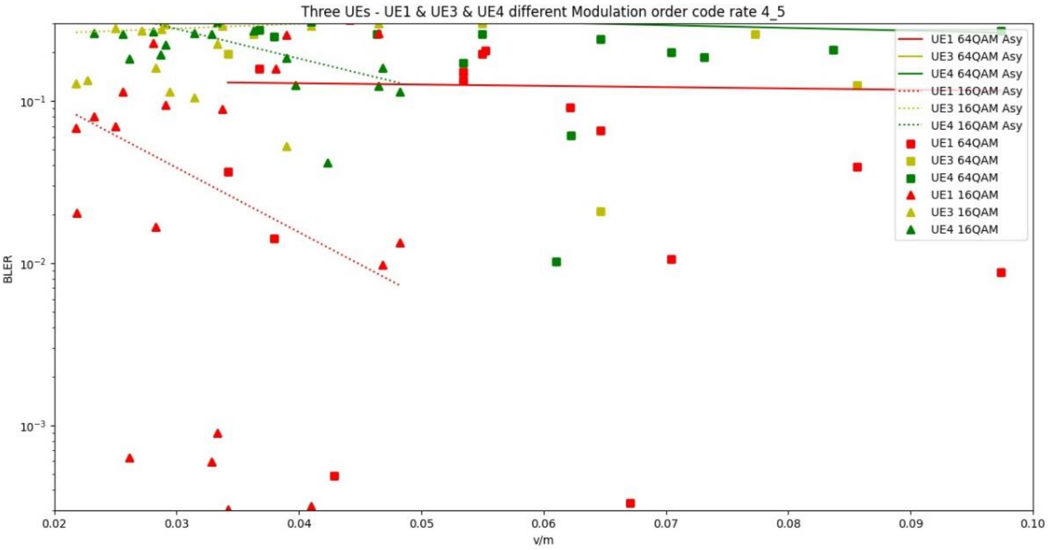


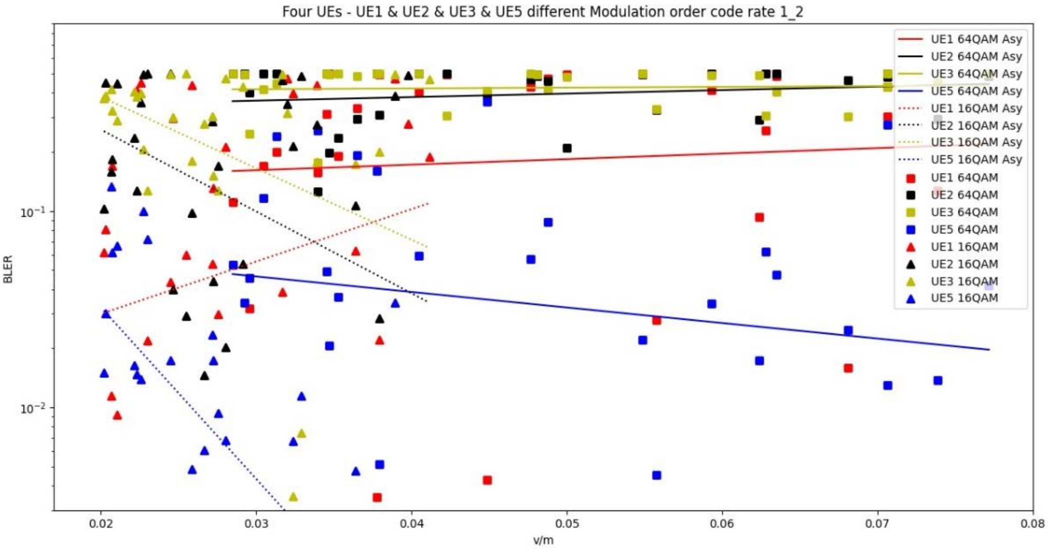
(b)

Figure 13 *BLER vs RF-EMF when UE1, UE3 and UE4 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*

From the above, with three active UE measured results, one observes that when using ZF precoding, the greater the number of users, the lower the quality of the beamforming hence higher BLER. Similar observations were found in Section 3.12 of D1 report. Also, a similar trend could be observed over the increase of BLER and RF-EMF with higher code rate.

3.2.1.4 Four active UEs

Figure 14 and Figure 15 show the 'BLER vs RF-EMF' plot for the comparison between different modulation order under the same code rate with 'UE1, UE2, UE3 & UE5', and 'UE1, UE2, UE4 & UE5' activated, respectively.



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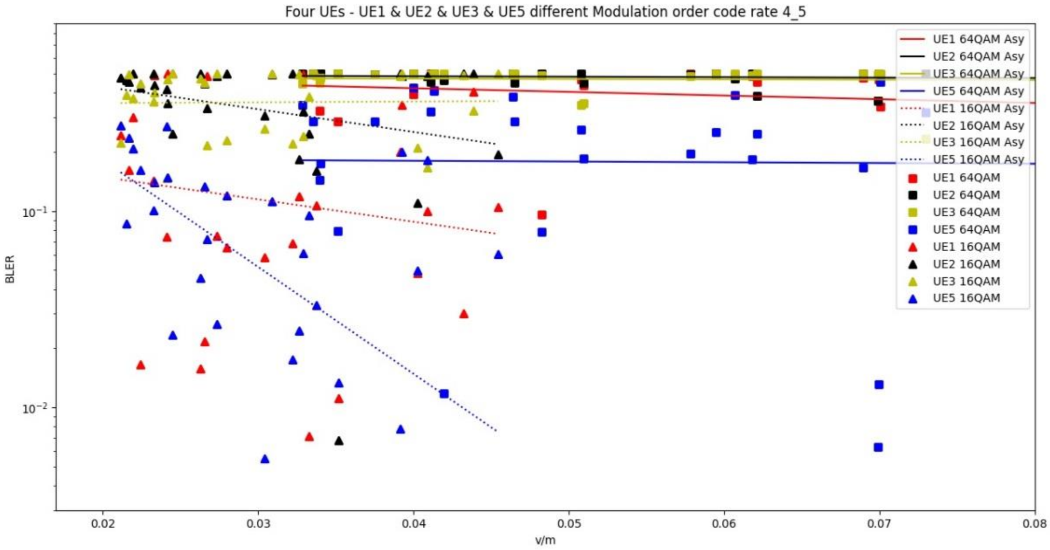

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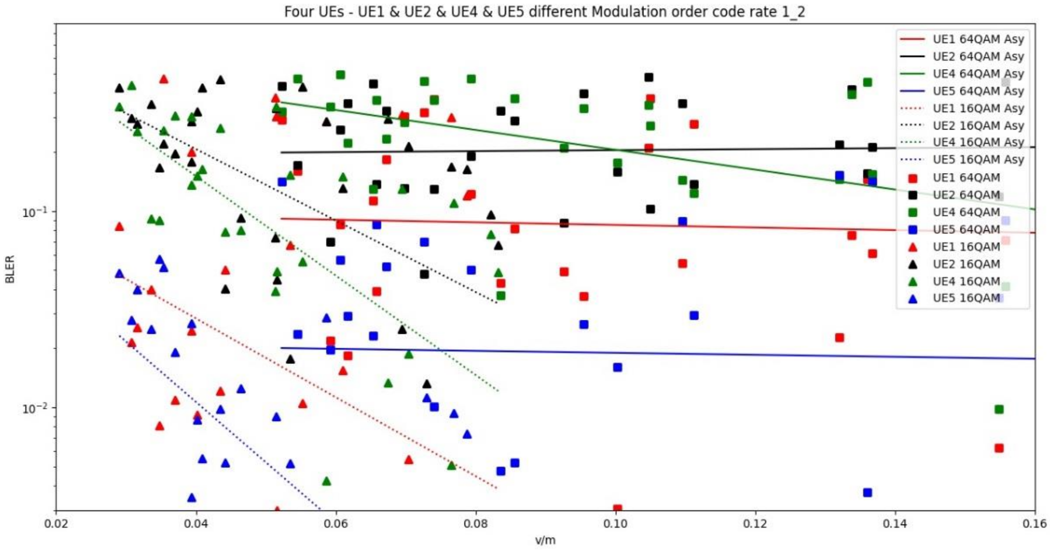
Figure 14 *BLER vs RF-EMF when UE1, UE2, UE3 and UE5 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*



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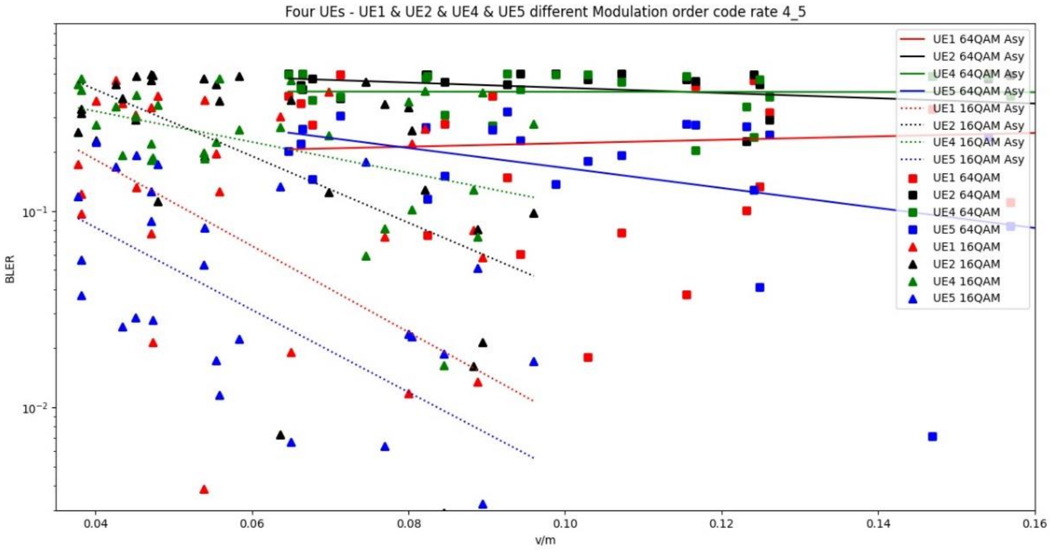


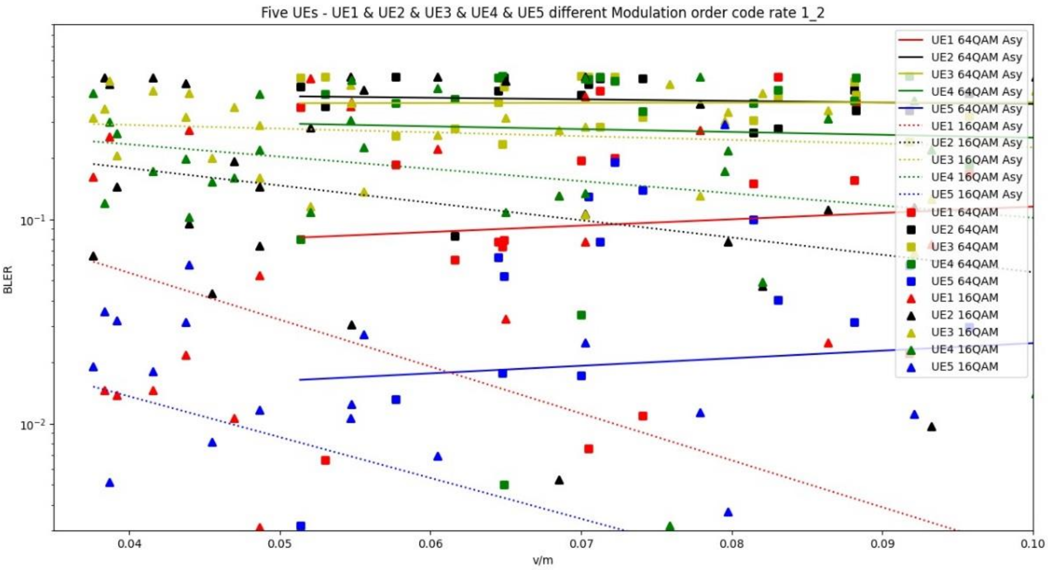
(b)

Figure 15 *BLER vs RF-EMF when UE1, UE2, UE4 and UE5 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*

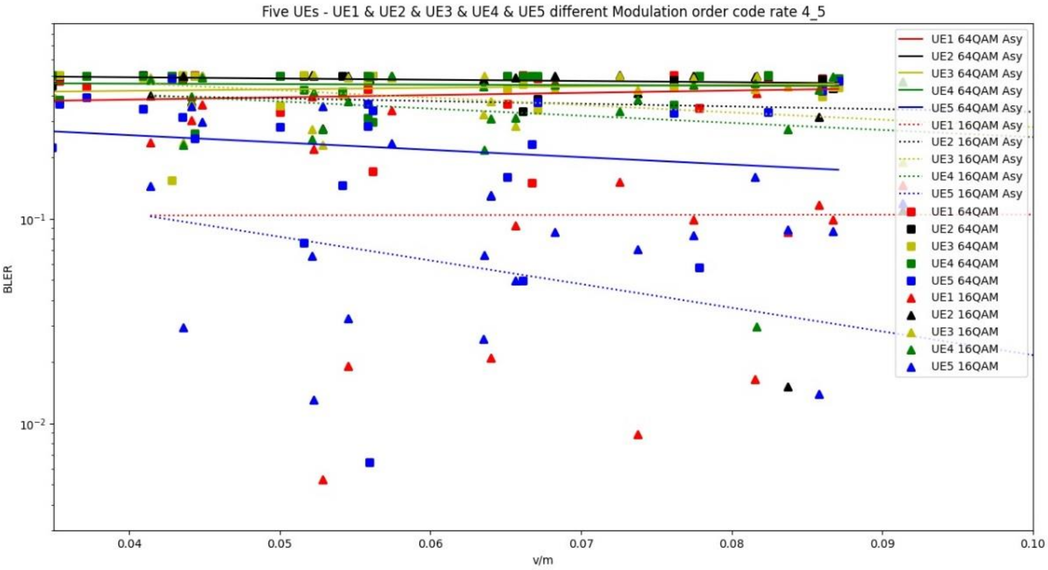
From the above with four active UE measured results, similar observations are found as those obtained in three UE measured results. i.e. when using ZF precoding, the greater the number of users, the lower the quality of the beamforming hence higher BLER. Also, a similar trend could be observed over the increase of BLER and RF-EMF with higher code rate.

3.2.1.5 Five active UEs

Figure 16 shows the 'BLER vs RF-EMF' plot for the comparison between different modulation order under the same code rate with all 'UE1, UE2, UE3, UE4 & UE5' activated.



(b)



(b)

Figure 16 *BLER vs RF-EMF when UE1, UE2, UE3, UE4 and UE5 are activated: Comparison between different modulation order for code rate of (a) 1/2; and (b) 4/5.*

From the above five active UE measured results, similar observations are found as those obtained in three and four UE measured results. i.e. when using ZF precoding, the more the users, the lower the quality of the beamforming hence higher BLER. Also, a similar trend could be observed over the increase of BLER and RF-EMF with higher code rate.

3.2.2 Number of active mMIMO Tx antennas

Considering varying mMIMO Tx power for one active UE (i.e. UE1) with modulation order of 64 QAM and convolution coding with code rate of 1/2, this section presents the measured ‘BLER versus RF-EMF’ plots for different number of active mMIMO Tx antennas. The MIMO transmission scheme in the mMIMO platform is the zero-forcing method. The plots show under different scenarios (e.g. modulation order, code rate) how the increase of mMIMO Tx power (hence the measured RF-EMF) effects the resultant BLER where the same colour dot and link show, respectively, the actual measured values and the fitted line. During the measurement campaign, the number of active mMIMO Tx antennas was set to operate with 96, 32 and 16, respectively, with Tx power level set to decrease from its default value down by 20 dB with a step of 2 dB between each decrement step. Five measurements were acquired at each step of the Tx power level. Note that the measurement of BLER is limited by noise floor vs. spectrum analyzer settings of Keysight Fieldfox. Figure 17 to Figure 19 show the ‘BLER vs RF-EMF’ plot for the number of active mMIMO Tx antenna of 96, 32, and 16, with UE1 activated with modulation order of 64 QAM and code rate of 1/2, respectively.

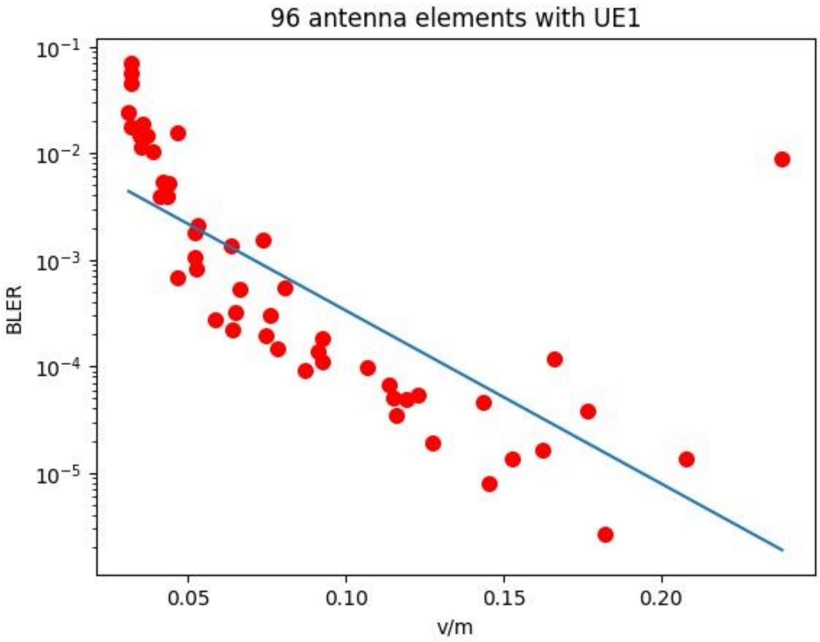


Figure 17 *BLER vs RF-EMF when UE1 is activated with modulation order of 64 QAM and code rate of 1/2 for 96 mMIMO active Tx antennas.*

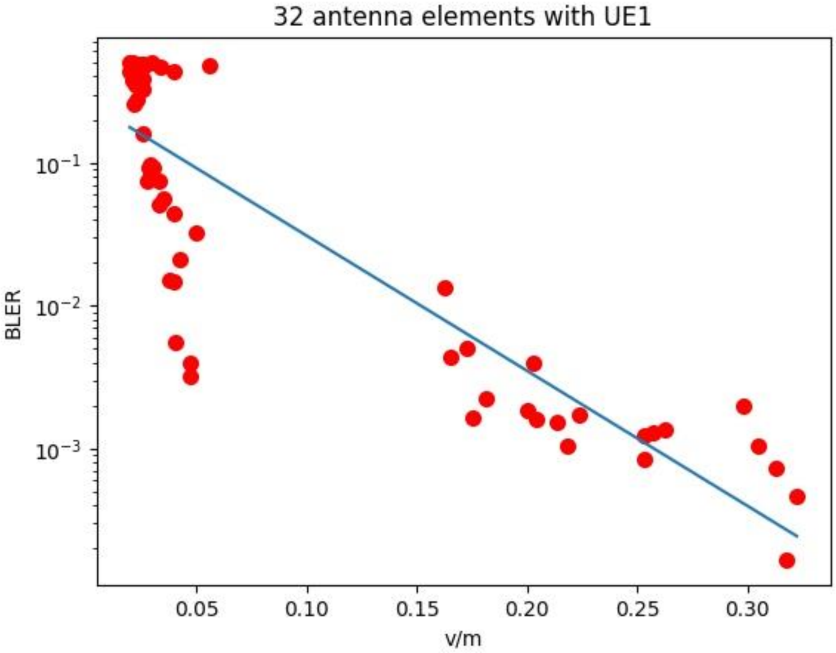


Figure 18 *BLER vs RF-EMF when UE1 is activated with modulation order of 64 QAM and code rate of 1/2 for 32 mMIMO active Tx antennas.*

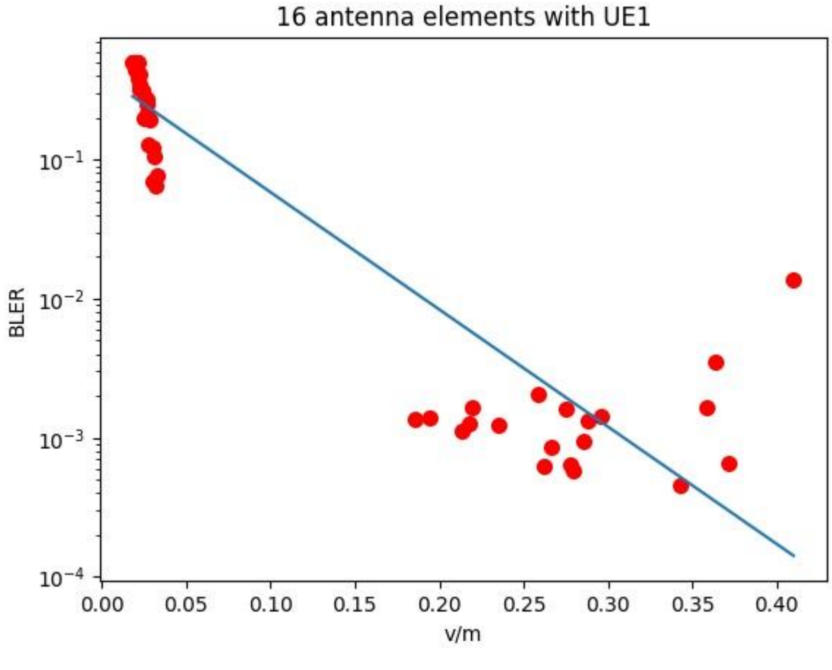


Figure 19 *BLER vs RF-EMF when UE1 is activated with modulation order of 64 QAM and code rate of 1/2 for 16 mMIMO active Tx antennas.*

Note that, at the receiving side, the probe was located beside the activated UE to capture the RF-EMF value. Hence, the array gain at the probe position is envisaged to be lower than UE since the ZF weight vector used in the mMIMO transmission is only optimized for the UE position. From all the above single active UE measured results, one observes that for the same RF-EMF level, BLER increases with smaller number of active mMIMO Tx antennas whereby for a fixed BLER threshold, the RF-EMF level decreases with a larger number of active mMIMO Tx antennas. This is because, a larger number of active mMIMO Tx antennas (i.e. larger array size) brings greater MIMO array gain. i.e. considering the same demodulation signal-to-noise ratio (SNR) at Rx side, the power of each Tx antenna element will be significantly reduced with a larger number of active mMIMO Tx antennas.

4 Conclusion

This evaluation report has presented the evaluation of how the stringent RF-EMF limits affect the 5G wireless communication performance. A measurement campaign has been carried out using the developed user-controllable mMIMO beamforming Tx system, Surrey UEs, and traceable RF-EMF measurement systems. The focus is given on the study of how the communication link performance between mMIMO BS and UE(s) are affected by the variation of the mMIMO BS Tx power, number of UEs, and UE data rate (by means of adjusting its MCS via modulation order and code rate). Based on the experimental-based evidence, the measurement results are analysed to enable insight and understanding regarding the evaluation of how the stringent RF-EMF limits affect the 5G wireless communication performance. The results could be assessed by either looking into a fixed BLER threshold or fixed RF-EMF so to study how 5G BS could react to varying radio conditions (e.g. using a link adaptation algorithm) by changing the relevant factors, e.g. MCS, mMIMO Tx Power, etc.

By varying the number of active UEs with fixed number of mMIMO Tx antennas, one observes that for the same RF-EMF level, BLER increases with higher code rate and modulation order whereby for a fixed BLER threshold, the RF-EMF also increases with higher code rate and modulation order. However, from the measured results for three to five active UEs, one observes that when using ZF precoding, the greater the number of users, the lower the quality of the beamforming hence higher BLER. By varying the number of active mMIMO Tx antennas with one active UE, one observes that for the same RF-EMF level, BLER increases with smaller number of active mMIMO Tx antennas whereby for a fixed BLER threshold, the RF-EMF level decreases with a larger number of active mMIMO Tx antennas.

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