Coexistence Testing: Comparing Conducted and Radiated Test Results

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Abstract—**In an era of ubiquitous wireless devices, ensuring their coexistence in shared electromagnetic environments has become increasingly critical. This paper explores the dynamics of coexistence testing and compares two coexistence test environments outlined in the ANSI/USEMCSC C63.27 standard: conducted and radiated-anechoic. The objective is to demonstrate how the results from two different test environments can be compared. We conducted a series of tests involving a commercial wireless Emergency Stop (E-Stop) system and IEEE 802.11 WLAN technology - two wireless technologies deployed in machine safety applications in industrial settings, including the mining sector. These tests provide insights into how the different testing environments can influence the outcomes of coexistence tests and how one can compare the results between two different test environments. The paper also presents an overview of general coexistence testing procedures.**

Index Terms—**Conducted test, Machine safety, Mining, Radiated test, Wireless Coexistence, WLAN**

I. INTRODUCTION

In the digital era, where wireless technology permeates every aspect of our lives, ensuring the harmonious operation of a myriad of electronic devices is paramount. Correspondingly, evaluating how well electronic devices operate in close proximity to others, particularly in environments dense with wireless signals, has become increasingly important. This evaluation is the goal of coexistence testing. In coexistence testing, the focus is on evaluating the performance of both the system under test and the other interfering, or "unintended," network. This is in contrast to immunity/interference testing, which is not designed to characterize a device's wireless link.

ANSI/USEMCSC C63.27 – 2021 [1] offers standardized methods to quantify a device's ability to coexist and evaluate wireless coexistence. This standard emerged in response to regulatory demands for a consistent testing approach across various industries, notably medical devices. It is a versatile standard, applicable across different sectors, frequency bands, and any set of wireless technologies. The standard incorporates four test methods: conducted, radiated-anechoic chamber, radiated open-environment, and multiple chamber tests. While the effectiveness of each testing methodology has been individually demonstrated [2]–[4], comparative results of these tests, except for the two radiated environments [5], are yet to be published.

This paper follows the procedure given in [1] to explore the essential role of conducted and radiated-anechoic coexistence test environments and presents a comparative analysis of these tests that has not been previously addressed in the literature. Our comprehensive analysis describes the wireless coexistence evaluation process for a use case in industrial machine safety. The evaluation involves identifying device functionalities related to its wireless capabilities, establishing criteria for functional wireless performance, arranging both intended and unintended network layouts, executing tests across different environments, and comparing the test results between the two environments. Through this exploration, this paper aims to determine how both conducted and radiated-anechoic coexistence test environments influence coexistence tests' outcomes and provide guidance on selecting the appropriate coexistence testing method for specific scenarios.

II. CONCEPTS OF CONDUCTED AND RADIATED ENVIRONMENTS

The two essential procedures at the core of coexistence testing are conducted and radiated tests [6]. Each test environment reflects different scenarios, unintended signal types, and device characteristics. Common to both are some definitions. Coexistence testing involves evaluating one device under test (DUT), or system under test (SUT), in relation to another DUT or SUT. The primary device or system is often referred to as the intended device or network, while the secondary device or system is often referred to as the unintended device or network.

In practice, conducted tests are typically used for DUTs with easily accessible coaxial RF ports. As described in Annex B of [1], the configuration uses power splitters/combiners, attenuators, and cables for each connection. Other radiated effects, such as multipath and antenna efficiency, are not directly replicated in this setup; however, the signal path can be tightly controlled. Conducted tests also have the advantage of not needing an anechoic chamber or large open-air range.

Radiated tests, on the other hand, involve emissions and reception of electromagnetic energy from a device over the air. Devices are physically separated in an anechoic chamber or an open environment, typically using a line-of-sight configuration. Anechoic chamber tests simulate free-space propagation conditions, which may differ from the actual deployment environment, where the devices are likely subject to propagation effects such as reflection, diffraction, and scattering. However, radiated tests include antenna and device-specific effects that are excluded from conducted tests, and can provide a better indication of the device's real-world performance.

In theory, both conducted and radiated test methods are expected to yield the same conclusions due to their fundamental principles. However, a direct comparison can get complicated since some factors are accounted for in radiated testing that are not accounted for in conducted testing (e.g., antenna effects). The two test environments also possess different system characteristics (e.g., cable and circuit losses) that must be accounted for. Once the difference in test systems and device factors are accounted for, the results between the two test environments should be comparable.

III. TEST PARAMETERS

In coexistence measurements, both the intended and unintended networks are monitored simultaneously for changes. The intended SUT here is a commercial-off-the-shelf (COTS) wireless Emergency Stop (E-Stop) system that operates in the 2.4 GHz Industrial Scientific and Medical (ISM) band and utilizes a frequency hopping spread-spectrum (FHSS) protocol. This system is composed of an E-Stop pushbutton unit that we will refer to as the "intended" device and an accompanying "receiver" device that we will refer to as the "intended companion" device, as described in [1]. The FHSS protocol used in the E-stop system consists of a narrowband carrier rapidly changing its frequency across the entire 2.4 GHz ISM band.

Choosing the unintended signal(s) necessitates careful consideration of the wireless systems and signals in the intended system deployment environment. The unintended signal(s) should be selected based on what the DUT is likely to encounter in its deployment environment. WLANs are becoming increasingly prevalent in industrial and mining applications, and an E-Stop system operating in the 2.4 GHz ISM band is likely to come across WLAN signals. Therefore, the unintended wireless technology considered here is an IEEE 802.11n WLAN link. The WLAN system is composed of an access point (AP), known as the "unintended device," and a client, known as the "unintended companion."

The device's functional wireless performance (FWP) must be determined before initiating any coexistence assessment. As defined in [1], FWP encompasses only the subset of a device's total functionality that utilizes its wireless features and would lead to unacceptable outcomes if impaired. Coexistence testing is restricted to impacts on the device's FWP. The E-Stop's FWP can be defined as the reliable transmission of an emergency signal, sending a signal upon device activation (when the E-Stop button on the intended device is pressed) and a reset signal upon device deactivation (when the E-Stop button on the intended device has been reset). Reliable transmission of the emergency signal can be compromised when the link quality of the E-Stop system is impaired. In this case, the action of the system is to generate an automatic, "fail-safe," device activation regardless of the state of the E-Stop button. When link quality is restored, the action of the system is to again reflect the current state of the E-Stop button. This fail-safe function is the actual condition measured during testing.

The next step in a coexistence assessment is to define key performance indicators (KPIs) to quantify the coexistence performance of the DUT and help ensure the test runs as expected, effectively evaluating the performance of wireless communication links. Here, the SUT is a straightforward system with the state of the pushbutton reflected in the state of a relay on the "controller." To measure that state, we connected the relay output of the "controller" to an LED indicator. This LED serves as the primary KPI for monitoring the link's status. During the coexistence test, we closely monitored the LED indicator for any changes in its state. The observed states included normal operation (indicated by a continuously lit LED), intermittent operation (characterized by periodic blinking of the LED), and failure (where the LED remained unlit). When the LED was continuously lit, the DUT could connect to the intended companion device. When intermittently blinking, the link between the two was not consistently usable. A complete link failure occurred when the LED remained off, and the link was broken. The E-Stop and reset signals could not be sent when the LED was off.

During the test, we monitored the WLAN link's throughput as the unintended signal's KPI to verify that the coexistence test was proceeding correctly. If we observed any drop in throughput or instability in the link, we paused the testing to reset the WLAN connection, ensuring accurate DUT interference characterization without prolonged disruption.

We also measured the intended-to-unintended ratio (I/U) at the point where the SUT's LED began intermittently blinking by monitoring the LED for 30 seconds for each configuration in the coexistence test. The I/U ratio is defined as the ratio of the peak received intended signal power to the peak received interference (unintended signal) power, measured at the spectrum analyzer and adjusted for system losses calculated at the DUT. Because we calculate this ratio at the DUT (as opposed to at another point in the test circuit) it can be used to compare the results of conducted and radiated tests.

Three key elements - time, frequency, and physical separation - affect interference and coexistence among wireless devices. Altering any of these can significantly impact the level of interference or coexistence experienced between devices, which is crucial in shaping the design of a test plan. Since the devices under consideration are geographically proximate, adjusting unintended signal parameters, like bandwidth and transmit power, could influence the FWP and determine the SUT's coexistence capability. We chose bandwidths of 20 MHz or 40 MHz and a maximum transmit power of 30 dBm because they represent common operational conditions of the unintended signal in the 2.4 GHz ISM band. To assess the impact on the FWP, we conducted tests using transmit powers of 30 dBm, 20 dBm, and 10 dBm. We also evaluated the SUT at 20 MHz and 40 MHz bandwidths.

IV. MEASUREMENT METHODS

Testing was performed using the coexistence test methods outlined in Annex B for the conducted test and Annex D for the radiated-anechoic test, as described in C63.27 [1].

The unintended WLAN signal is generated using a COTS development board functioning as the AP, along with a COTS WLAN client device that is connected to a computer via USB. The WLAN development board has open-source software that allows for the adjustment of the transmit power and channel bandwidth. It is programmable to emit power up to 30 dBm and supports IEEE 802.11n signals for channel bandwidths of 20 MHz and 40 MHz in the 2.4 GHz ISM band. WLAN traffic was created using Transmission Control Protocol (TCP), achieving maximum data throughputs of 65 Mbps for 20 MHz channel bandwidth and 130 Mbps for 40 MHz channel bandwidth, effectively simulating full channel utilization. Data were transmitted from the AP to the client (downlink transmission), limiting the amount of traffic from the client to the AP (uplink). To help reduce the impact of the uplink signal on the outcome of the coexistence test, a 30 dB attenuator was attached to the client.

To simulate path loss between the intended device (pushbutton), intended companion (controller), and unintended devices, we systematically adjust the programmable attenuator connected to the intended device and its companion. The state of the E-Stop link quality was then continuously monitored by visually observing the LED as adjustments were made to the attenuators. The adjustment of the attenuators was carried out in the following manner. The pushbutton attenuation was set to 0 dB. Then, the controller attenuation was incrementally increased from 0 dB to 90 dB in 1 dB steps, during which the E-Stop link quality state was observed and recorded over 30-second intervals. This procedure was repeated, with gradual increases in the pushbutton's attenuation up to 35 dB, with 5 dB steps, while repeating the adjustments on the controller. Finally, the repeatability and reproducibility of the tests validated the measurement results for both test methods.

In both the conducted and radiated cases, the system losses between each device were measured either with a vector network analyzer (for the radiated test) or a spectrum analyzer and signal generator (for the conducted test). These system loss measurements capture the test circuit's insertion loss between ports. In the radiated case, the loss measurements include the effects of the antennas and over-the-air propagation.

A. Conducted Test

A diagram of the conducted measurement setup is shown in Fig. 1. Each device – the WLAN AP, WLAN client, pushbutton, and controller – was placed in its individual shielded box to ensure no unintended cross-talk between the intended and unintended links. These shielded boxes' radio frequency (RF) ports are connected to a programmable attenuator attached to a bidirectional four-way power splitter/combiner. Each of the four output ports of the splitter/combiner is connected to each one of the other devices, including the spectrum analyzer used to monitor the intended and unintended signals and measure the I/U ratio. A photograph of the setup is shown in Fig. 2.

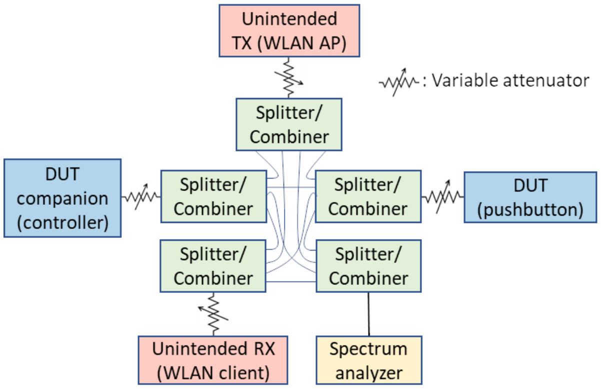

Fig. 1: Layout of the conducted measurement setup

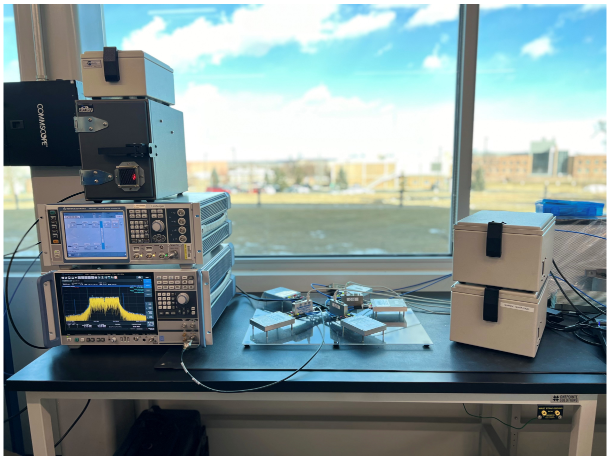

Fig. 2: Photograph of the conducted measurement setup.

B. Radiated Test

All the radiated experiments occurred inside an anechoic chamber with interior dimensions of 3.0 m by 2.3 m by 2.1 m (L, W, H; absorber tip to absorber tip). Setting up the devices inside an anechoic chamber ensures that the test is performed in an environment isolated from ambient signals outside the chamber and that all devices in the test have a constant propagation channel. Fig. 3 displays a test setup diagram. The purpose of locating the pushbutton in close proximity to the WLAN AP is to simulate the real-world case where the WLAN device and the pushbutton are nearly co-located. In practice, this could be a person carrying both the E-Stop pushbutton and a WLAN device. The simulated distance between them changes with increased attenuation during the coexistence test.

The WLAN AP and client were each placed inside a small shielded enclosure within the anechoic chamber. The E-Stop pushbutton and controller were placed inside their shielded enclosures but outside the anechoic chamber. The shielded enclosures helped ensure any leakage stayed inside the box and did not reach the other devices. Each of the four devices is connected to its own omnidirectional antenna with a theoretical

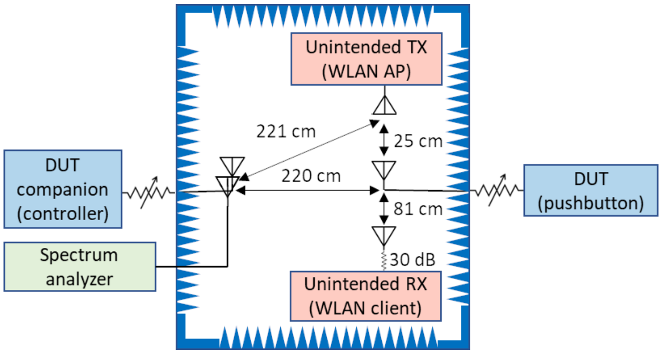

Fig. 3: Layout of the radiated measurement setup

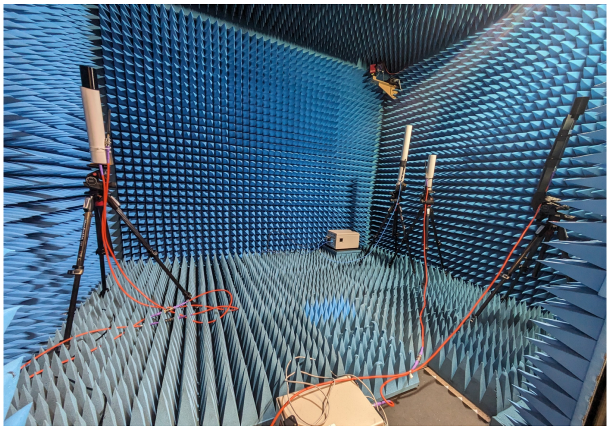

Fig. 4: Photograph of the radiated measurement setup in the anechoic chamber.

gain of 2.15 dBi, as shown in Fig. 4. Two programmable attenuators are connected between each of the RF ports of the shielded boxes containing the pushbutton and controller, and their antennas. The intended and unintended signals were monitored and measured using a spectrum analyzer placed outside the anechoic chamber and connected to its own omnidirectional antenna inside the chamber.

The variable attenuators are computer-controlled via USB for both conducted and radiated tests. The systems were calibrated, and each path's loss was measured. Using this setup, the intended link quality susceptibility to the unintended signal is varied by increasing the attenuation level, which emulates additional physical line-of-sight distance in a real-world environment.

V. RESULTS

Fig. 5 uses color coding to demonstrate how varying attenuation at the intended devices changes the E-Stop link quality. It displays the effect of WLAN interference on intended link quality, showing how varying WLAN power levels and WLAN bandwidths affect the intended link quality. It also demonstrates the impact of the coexistence test setups. While the x-axis shows the set attenuation values at the controller plus the system loss, indicating the combined loss that the signal experiences after being transmitted, the y-axis exhibits the set attenuation values at the pushbutton. Three key states of the E-Stop link are depicted: "ON," "INT" (intermittent), and "OFF," each represented by a different color. The green areas illustrate where the E-Stop link is stable and reliable, indicating optimal conditions for an E-Stop link connection. Yellow areas mark the "INT" state, signifying potential false-tripped scenarios where the E-Stop connection may be subject to intermittent disruptions or variations in signal strength. Lastly, the red areas mark the "OFF" state, representing conditions under which the link is completely lost. Each plot also contains a black line indicating the maximum path loss ($\approx$ 126 dB) the SUT can sustain before the link is broken *regardless* of the unintended signals and test environments.

When interpreting these results, the shape and size of yellow regions are important as they vary among plots. They essentially show the impact of the WLAN signal on the intended link. The plots in Fig. 5 can be compared to consider the impacts of both WLAN power and bandwidth on the performance of the SUT. As the power of the WLAN AP decreases, we see the yellow region of both test environments getting smaller. This is to be expected as a lower AP power should cause less impact on the intended link.

Similarly, the impact on the intended link decreases as the WLAN signal bandwidth decreases. Again, this is expected as the 20 MHz signal occupies a significantly lower portion of the SUT's channel. For further interpretation, one could convert these dB values to distance using a desired propagation model. This would put the results of the coexistence test in terms of distance (e.g., distance between the SUT and the AP at the time the LED begins intermittently flashing).

Comparing the conducted and radiated plots reveals the extent to which the coexistence test setup influences the intended system link quality. In general, the radiated tests show a smaller yellow region. But does this mean that the SUT performs better in a conducted test than in a radiated test? The next section explores this question.

Fig. 6 shows the measured I/U ratio when the SUT starts to fail vs. the total loss in the intended link for either conducted or radiated setups. The y-axis is in terms of the intended signal peak power ("I") vs. the unintended signal peak power ("U"). All data in this plot are referenced to the plane of the pushbutton. Importantly, each test case plotted follows a similar trend. The steep vertical transition at the SUT's path loss limit is 126 dB, approximately equal to the receiver's sensitivity. Reading the plot, for a total loss of 110 dB in a conducted setup and a WLAN bandwidth of 40 MHz, the I/U ratio is -36 dB for a WLAN transmit power of 30 dBm. This indicates that for a total loss of 110 dB, the SUT starts to fail when the intended received power is 36 dB *below* the unintended received power from the WLAN AP. For WLAN transmit powers of 20 dBm and 10 dBm, the I/U ratio is -33.5 dB. For radiated tests with the same total loss and WLAN bandwidth, the I/U ratios are -38 dB and -34 dB for 30 dBm and 20 dBm WLAN transmit powers, respectively. This agreement is promising, but a closer look is necessary.

Note that the red lines extend over a wider range on the x-axis compared to the blue lines, indicating that the conducted measurements covered a larger range of attenuation (i.e.,

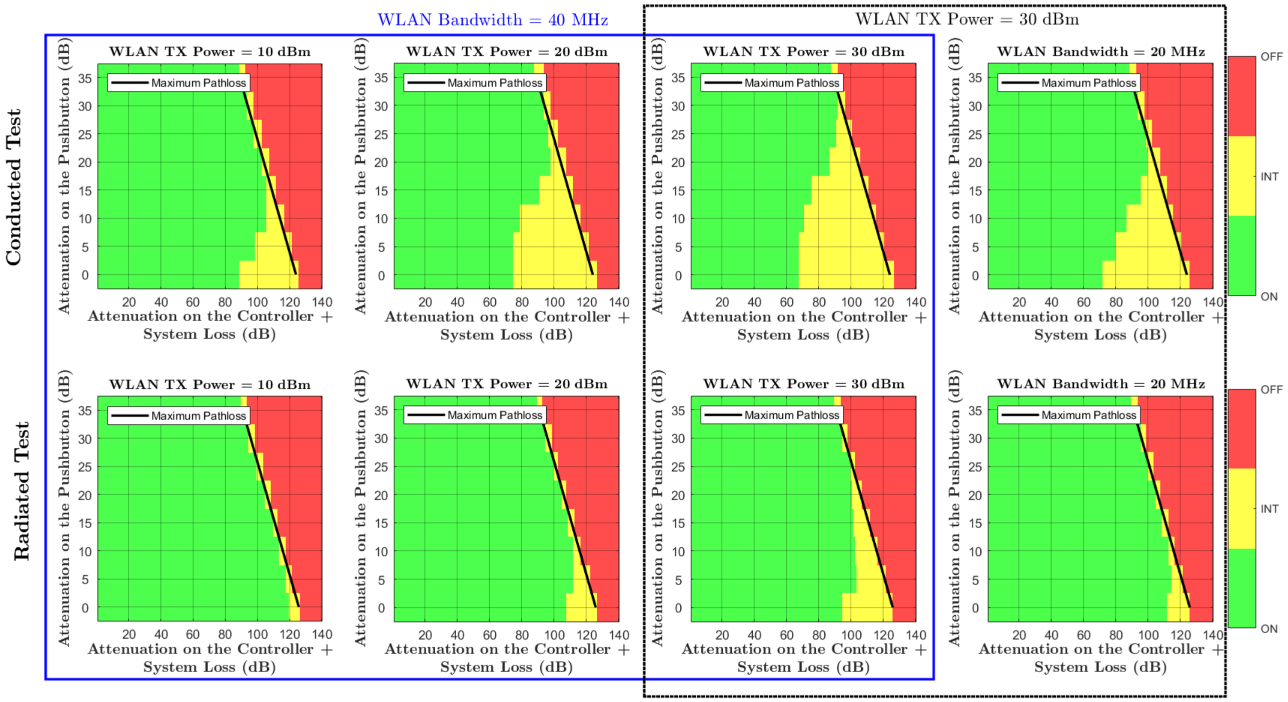

Fig. 5: E-Stop link quality across various WLAN TX powers and WLAN bandwidths for both conducted and radiated tests. Plots within the solid line rectangle represent scenarios with a WLAN bandwidth of 40 MHz. Plots within the black dotted rectangle are associated with a WLAN transmitter power of 30 dBm.

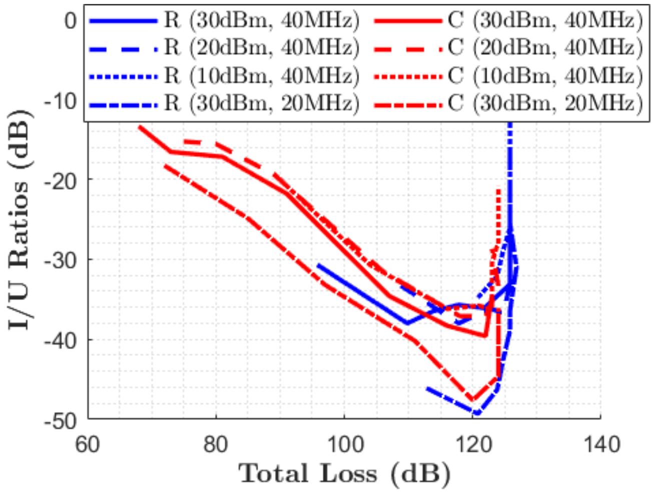

Fig. 6: The I/U ratio versus the total loss, at the point where the SUT's LED began blinking, for radiated (R) and conducted (C) test configuration setups.

possible distances between devices) than was covered in the radiated testing. The conducted test setup's extended capability results from lower system losses and no loss due to antennas and over-the-air propagation. Systematic uncertainties are not considered, as we focus on measuring relative differences between the conducted and radiated-anechoic test environments.

VI. DISCUSSION

One approach to directly compare test results between radiated and conducted measurements is to replicate the same losses in both test environments. To achieve this, we performed an additional test specifically designed to replicate the losses in each environment. That is, we set the variable attenuators in the conducted test circuit to match the actual system losses measured in the radiated setup. Each link is one of the six connections between intended and unintended transmitters and receivers. We noted each device as S_i: S_1 for the WLAN transmitter, S_2 for the E-Stop transmitter, S_3 for the E-Stop receiver, and S_4 for the WLAN receiver.

The identified differences in losses will then be applied as additional attenuation to each device involved in the communication links. To ascertain the required attenuation for each device, we formulate a system of equations consisting of six equations (communication links) and four variables (devices),

$$\begin{aligned} S_1 + S_2 &= 11, & S_1 + S_3 &= 30.6, & S_1 + S_4 &= 13.4, \\ S_2 + S_3 &= 39.8, & S_2 + S_4 &= 20.4, & S_3 + S_4 &= 28.7 \end{aligned} \tag{1}$$

The rank of the matrix containing the above equations is four, suggesting some of the equations are dependent on others. Based on our analysis, the S_4 to S_2 and S_4 to S_3 links are not independent and are influenced by the other existing links in the system, indicating the interdependence within the system. Therefore, the four independent equations can be used to determine the additional attenuation values for each device. Ideally, if all six equations were consistent, the solution obtained from the four independent equations should also satisfy the other two. However, these calculated values do not accurately account for the losses between the unintended receiver and the intended transmitter/receiver, implying that the system of equations as a whole is inconsistent, and the remaining two equations may represent conditions that contradict the first four. Furthermore, this indicates that the unintended receiver

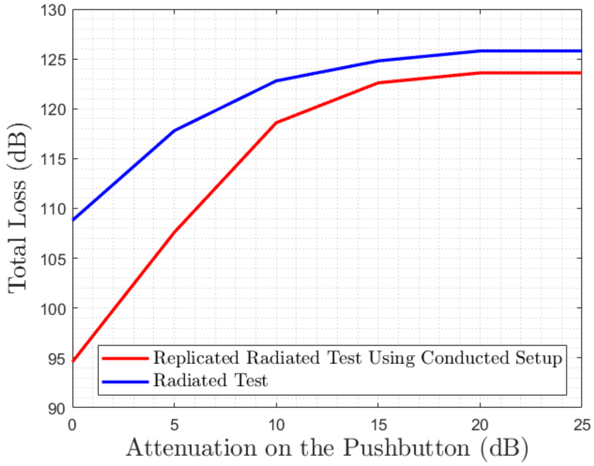

Fig. 7: System losses when replicating radiated measurement in the conducted test setup.

(WLAN client) has an impact on the test even though most of its traffic is downlink. This suggests that relying solely on the total loss may not provide a comprehensive understanding of the test. Total loss quantifies signal attenuation but it does not account for other critical factors like receiver behaviors under varying signal conditions, which significantly impact the coexistence performance. It may be possible to resolve this issue if the conducted test circuit is redesigned. This is the subject of future work.

Figure 7 shows how close we were able to get the losses between the conducted and radiated test circuits. This difference is due to the series of dependent equations described above.

Instead of comparing data in terms of total loss, we can compare them strictly by the peak powers of the intended and unintended signals present at the pushbutton at the time the link begins to fail. This comparison is shown in Figure 8. These results show close agreement - with deviations typically within a few dB - between the radiated and replicated measurements, demonstrating reliable replication accuracy. Better agreement than this is not expected due to measurement repeatability, which is estimated to be 1-3 dBm of signal power. This plot indicates that when the pushbutton is presented with a specified intended and unintended power level, *regardless of the system losses* it behaves nearly the same way in either a conducted or radiated test environment.

To summarize, this analysis shows that to compare coexistence test results from two different environments, one must use the signal power levels measured at a specified reference plane in the test circuit, which is a designated point where measurements are consistently taken for accurate comparison.

VII. CONCLUSION

Two coexistence measurement methods – conducted and radiated-anechoic – based on the C63.27 standard, are examined to investigate the impact of the coexistence test setups on the test's outcome. This work provides insights into how different testing environments can influence the outcomes of coexistence tests and shows how the results between the two test environments can be productively compared. The influence of using actual antennas in space (radiated-anechoic) versus approximations in RF circuits (conducted) is evident. In addition, losses between the two methods are found to be challenging to match. However, there is good agreement between the two test environments when looking at the power levels present at the device of interest. Though good agreement was shown, future work will investigate redesigning the conducted test circuit to offer better control of the losses between devices.

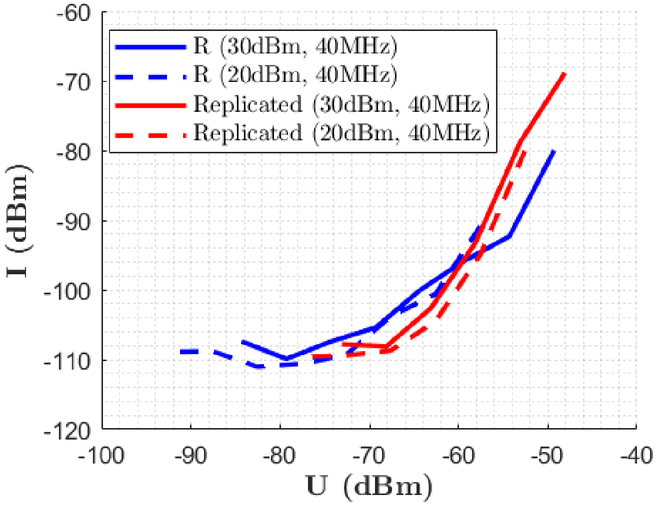

Fig. 8: Comparison of the received power between the radiated test (R) and the scenario replicating radiated losses using the conducted test setup (Replicated).

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), or the Department of Commerce (DOC). Mention of any company name or product does not constitute endorsement by NIOSH or DOC.

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