Verification of Coexistence Measurement Methods: Radiated Anechoic and Open Environment

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***Abstract*—With an abundance of wireless devices saturating daily life, the ability of devices to coexist among other devices is of increasing interest. While standards are starting to incorporate coexistence measurements, the robustness of coexistence measurement methods is still an area of active research. To demonstrate the robustness of the multiple test methods, a series of measurements needs to be conducted that compare a measurement methods. Ideally, if the same coexistence test is performed by use of each of the four methods, the end result should be the same. Here, we compare two popular radiated test methods: an anechoic chamber test and a radiated open-environment test. Both methods are part of the ANSI C63.27 standard. We examine the impact two of the possible environments may have on the outcome of a coexistence test. For this, we use Bluetooth low energy and Wi-Fi networks. Overviews of generalized coexistence testing and future work are also presented.**

I. Introduction

With the number of wireless devices that operate in the industrial scientific and medical (ISM) band growing at a rapid rate, coexistence testing methods are necessary to ensure device functionality in a crowded RF environment. Depending on the device under test's (DUT's) intended use, the coexistence requirement could be a safety concern (e.g., for a medical device), or a general-use concern (e.g., to ensure the end user's experience is acceptable). Regardless of the DUT's intended use, the goal of coexistence testing is to examine how well the device can perform in a crowded RF environment.

While interference testing has been studied extensively in past works and standards [1] [2], coexistence is a slightly different problem. Coexistence is defined as the ability of two or more spectrum-dependent devices or networks to operate without harmful interference [3]. With coexistence testing, the performance of both the DUT and the unintended network are examined. This differs from interference testing, where typically only the DUT is considered. The inclusion of both networks are important as the RF spectrum is becoming increasingly crowded and thus a more sought-after resource. In an attempt to establish a consistent set of coexistence measurement methods, the upcoming ANSI C63.27 standard provides a procedure for quantifying a device's ability to coexist [4]. Four test methods have emerged in the draft standard: conducted test, radiated anechoic test, radiated open-environment (ROE) test, and a hybrid/two-chamber test. Though the robustness of each test method has been demonstrated individually, results comparing the test methods has yet to be published. For example, if one lab tests a DUT by use of an anechoic chamber test, and another tests the same DUT by use of the ROE test, how close will the results be? This is the question we examine here for two of the test methods.

The coexistence methods themselves and the detailed test planning steps are not described here. Instead, we focus on the test environment and layout of the DUT and unintended network. We expect that by changing the layout of networks, the environment in which the test is performed, and by repeating the measurements, the results will be similar. If true, this would indicate that the layout of the devices and the test environment does not play a critical factor in the outcome of measurements. However, if significant variations in the measurements are observed, then either the environment or the layout could be impacting the final results.

II. General Coexistence Measurements

In true coexistence measurements not only is the DUT monitored for changes but the unintended network is also measured simultaneously. These coexistence measurements look at multiple parameters to quantify the performance of wireless communication links. Here, we look at test layouts in the environment and the robustness of the radiated anechoic and ROE methods. The anechoic environment is used as a baseline to measure the coexistence capabilities between the networks while the ROE can better approximate a real-world deployment environment. In the work presented here, the contributions of the DUT (and its network) are not quantified. Only the DUT's ability to perform in the presence of an unintended network is examined.

Interference and coexistence between wireless devices is affected by three parameters: time, frequency, and physical separation. By modifying any one of these parameters we can influence the level of interference/coexistence between devices. Since devices of interest are relatively close together geographically, the use of power, network throughput, and frequency separation between DUT and unintended network's channels are varied to measure the coexistence capability of a DUT. Here, the DUT uses a Bluetooth Low Energy (BLE) link between two devices, one of which is the DUT and the

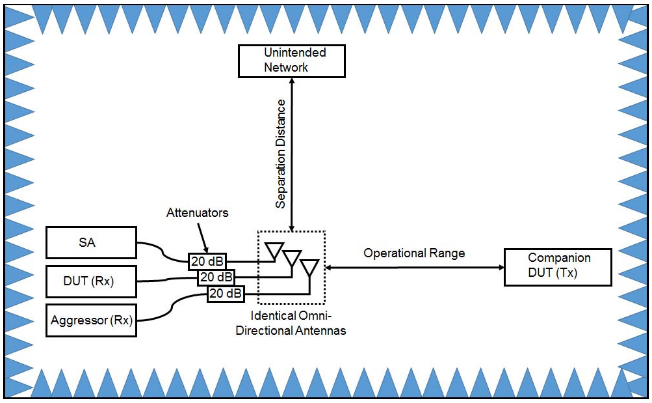

Fig. 1. Setup 1 - Block diagram used in both radiated anechoic and ROE.

unintended network uses a Wi-Fi link. For the coexistence test shown in Figure 1, there are several test parameters measured and recorded: packet error rate (PER), RF power in the environment, reported Wi-Fi received RF power, intended network throughput and frequency, and PER of the DUT network. Since the BLE link is what the DUT utilized, the PER is used as the primary metric for coexistence. On the unintended network, both throughput and transmitted power are recorded. A vector signal transceiver (VST) is used in spectrum analyzer mode to monitor the RF environment and the data recorded.

There are several different test parameters used to measure the coexistence between intended and unintended networks. Parameters include (but are not limited to): signal to interference ratio (SIR), throughput, and frequency. SIR is defined as the ratio of the averaged received carrier power and the averaged received interference power.

While this paper only discusses anechoic and ROE methods, it is important to note that there are a total of four possible test methods: conducted, radiated anechoic, ROE, and hybrid/two chamber (a mix between conducted and radiated involving two coupled anechoic chambers). The design of the DUT will play a significant role in determining which method is most appropriate and which case is appropriate for testing.

Conducted testing is the simplest setup and is designed for DUTs where the RF port(s) are accessible to those performing the test. Here, transmission lines, attenuators, power splitters, and combiners are used for all connections in the test setup. This test setup does not account for multipath, path loss, antenna efficiency and other radiated effects. The radiated test setup is done in an anechoic environment or an ROE with the devices spaced apart either line of sight (LoS) or non-line of sight (NLoS). The radiated test methods allow for some flexibility in recreating the deployment environment. Recreating the environment during the coexistence test can yield results that are more likely to predict in-field performance. Where strict control and isolation between the DUT and unintended network are desired, the two-chamber method can be of use.

III. Measurement Setup

The experimental setup consisted of an IEEE 802.11 access point (Wi-Fi access point), an IEEE 802.11 client (Wi-Fi client), and an unidirectional IEEE 802.15 link (BLE link). The first test method was the radiated anechoic shown in Figure 1. The anechoic chamber helped to ensure that outside disturbances were not having an impact on the wireless links.

The second method tested is the ROE shown in Figure 3. Here, two network layouts are tested and compared to the anechoic test results. The experimental setup was automated so that repeated measurements of the same configuration could be done and the data stored.

Both the Wi-Fi and the BLE wireless networks are implemented with commercially available off-the-shelf development boards. Coexistence testing with the Wi-Fi development boards requires control over the transmission power, throughput, and Wi-Fi channel. BLE development boards must report back the PER to the computer. Further, the BLE development boards have their channel number fixed and manually selected during the SIR and throughput tests. The values for PER are reported back in percent. The percentage value is calculated from the number of packets decoded with errors compared to the total number sent. If there are no packets received then, we assume that all packets are lost due to the unintended network (Wi-Fi), thus giving a PER of 100%.

For each setup environment, there are three separate test runs: SIR, throughput, and frequency tests. In the SIR test the Wi-Fi power is increased from 1 dBm to 9 dBm in increments of 1 dBm, with BLE transmission power and frequency held constant. In the throughput test, IEEE 802.11n standard was used with Wi-Fi throughput increased from 1 Mbps to 100 Mbps adjusted non-linearly as follows: 1-25 Mbps incremented by 1 Mbps, 25-55 Mbps incremented by 5 Mbps, and the last increment sets the Wi-Fi throughput to 100 Mbps. The BLE transmission power and frequency are held constant for the throughput test. Finally, for the frequency tests, Wi-Fi transmission power, throughput, and BLE transmission power are held constant while the BLE channel is adjusted from 1-37.

A. Anechoic Chamber Test Setup

A block diagram showing the anechoic chamber test setup is shown in Figure 1 and pictured in Figure 2. Three identical omni-directional antennas are placed 10 cm apart from each other. The received signals are recorded on a VST, the DUT receiver, and by the unintended network receiver. With this setup the susceptibility to interference is varied by the separation distance and the operational distance. The operational distance is determined by the received power level at the DUT receiver. This distance may be adjusted to achieve a -60 dBm power level at the DUT receiver, with the unintended network disabled. Separation distance of the Wi-Fi network is ideally set so the SIR curve has no interference until half the Wi-Fi channel throughput is utilized.

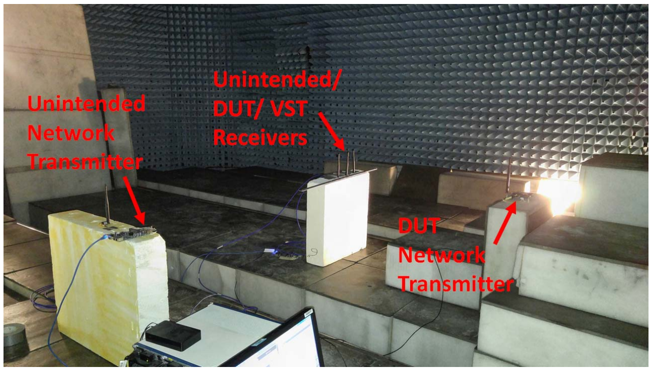

Fig. 2. Radiated anechoic Test Setup 1.

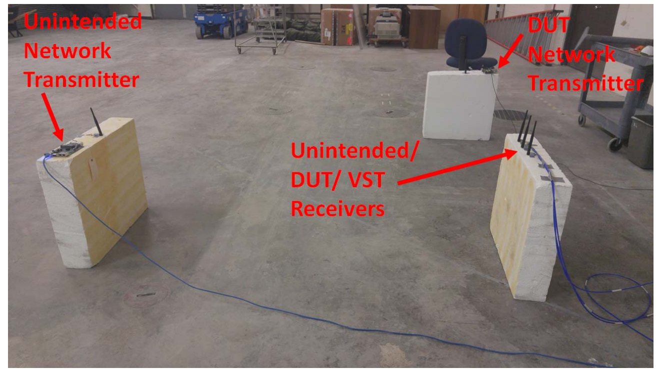

Fig. 4. Radiated Open-Environment Setup 1.

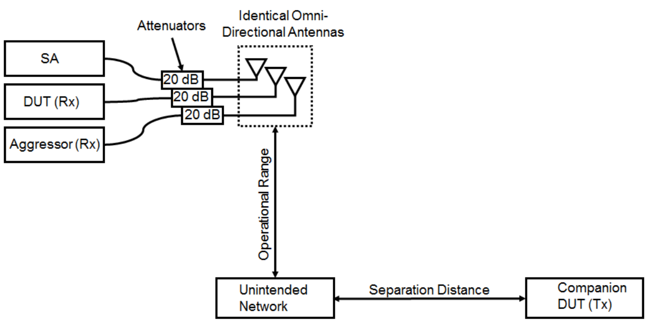

Fig. 3. Setup 2 - Block diagram used in ROE.

TABLE I
SUMMARY OF NETWORK LAYOUT AND ENVIRONMENTS

	Setup 1 - ROE	**Setup 2 - ROE**	**Setup 1 - Anechoic**
Network Layout #	1	2	1
Environment	ROE	ROE	Radiated Anechoic
BLE Parameters	PER	PER	PER
Wi-Fi Parameters	Throughput, Rx RSSI	Throughput, Rx RSSI	Throughput, Rx RSSI
Test Type	SIR, Frequency, Throughput	SIR, Frequency	SIR, Frequency, Throughput

B. Radiated Open-Environment Lab Test Setup

For the ROE setup, two different measurement setups were used. The first, test layout is identical to the setup in the anechoic chamber test. (See Figure 1.) The second test setup is shown in Figure 3 and pictured in Figure 4. Three identical omni-directional antennas are placed 10 cm apart from each other. The received signals are recorded on a VST, the DUT receiver and by the unintended network receiver. With this setup, the level of interference is adjusted by changing the separation distance and the operational distance. The operational distance is determined through the power level received at the DUT receiver. This distance may be adjusted to achieve a -60 dBm power level at the DUT receiver. Separation distance of the Wi-Fi network is ideally set so the SIR curve has no interference until half of the Wi-Fi channel throughput is utilized.

A summary of the network layout and test environment used is shown in Table I. Network layout is shown in Figure 1 and Figure 3. The BLE and Wi-Fi parameters that are measured for each test environment are listed in Table I.

IV. DATA

The recorded test data are averaged over the total number of repeat test runs performed for each test. Table II shows the minimum and maximum standard deviation for each test; in this case 10 test runs. The minimum deviation occurs when the PER is at 100% since the Wi-Fi signal dominates in power and throughput. The maximum deviation occurs roughly at 50% PER. This is likely due to variations in the Wi-Fi CCA. The computed average is plotted and the standard deviation is shown in Table II. Here, the averaged data are shown in three subsections: PER, Wi-Fi throughput and calculated difference between PER and Wi-Fi throughput.

Because PER is constrained to the bounded interval [0,1], confidence intervals based on a normal approximation can incorrectly fall outside of the valid range. To address this problem, confidence intervals were estimated with the aid of a logit transformation, following [7]. First, the logit function, which maps the interval [0,1] to the real line, was applied to the PER. Next, a 95% confidence interval for the mean logit-transformed PER was estimated with the usual approach based on a normal approximation. Lastly, the confidence interval in logit space was transformed back to PER with the inverse logit transformation (a.k.a. the logistic function). The resulting confidence interval for mean PER was consequently constrained to the interval [0,1], i.e., 0-100% when multiplied by 100.

A. Packet Error Rate Results

Figures 5 - 7 show the averaged PER for radiated anechoic and ROE. Figure 5 shows how the PER is affected by increasing the Wi-Fi transmit power on the unintended network. All device layouts and environment tests have a fixed number of discrete test increments. These increments are referred to as a test run number.

TABLE II
STANDARD DIVINATION OF PER

		Min(%)	Max(%)
Setup 1 - Anechoic	SIR	0.1133	1.6461
	Frequency	0	0.7457
	Throughput	0.1286	0.86
Setup 1 - ROE	SIR	0.1336	4.4065
	Frequency	0	2.7409
	Throughput	0.2104	5.7067
Setup 2 - ROE	SIR	0.0801	1.8805
	Frequency	0	0.9182
	Throughput	N/A	N/A

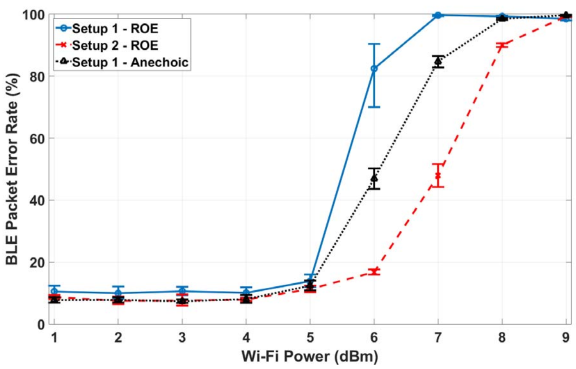

Fig. 5. SIR test - Average PER results.

Figure 6 shows the effects on PER when the BLE channel overlaps with a Wi-Fi channel. When the DUT transmits in the same band as the unintended network, the PER is high. When transmitting outside the unintended networks band there is little to no PER.

Figure 7 shows the effects of increasing the unintended network's throughput. The PER of the DUT increases as the Wi-Fi throughput increases, as expected.

B. Wi-Fi Throughput Results

Figures 8 - 10 show the averaged Wi-Fi throughput for radiated anechoic and ROE. The development boards that were used implement a version of the IEEE 802.11n standard. Therefore, a clear channel assessment (CCA) is done before each throughput test begins. If too much RF power is detected the throughput will be lowered to maintain the quality of the communication link.

For the SIR and frequency test, Wi-Fi throughput is held constant. The recorded Wi-Fi throughput is shown in Figure 8 and 9. Figure 10 shows the configured throughput versus that throughput measured by the Wi-Fi boards.

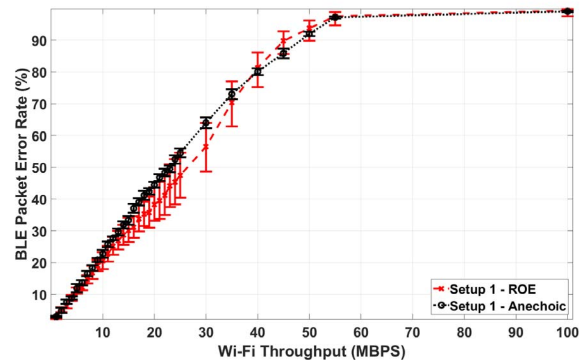

Fig. 7. Throughput test - Average PER results.

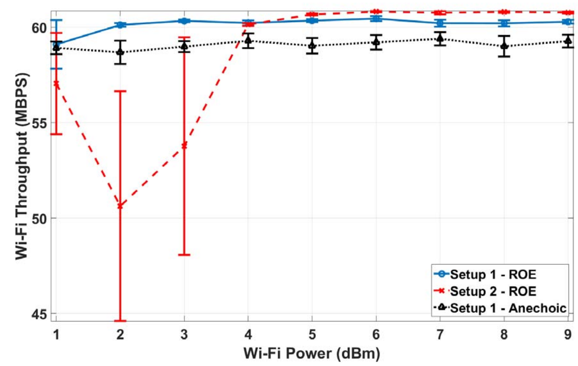

Fig. 8. SIR test - Average Wi-Fi throughput results.

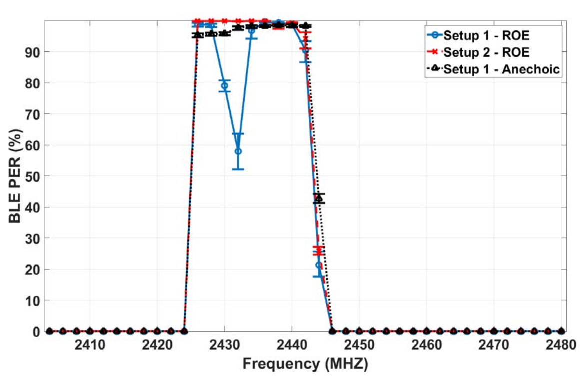

Fig. 6. Frequency test - Average PER results.

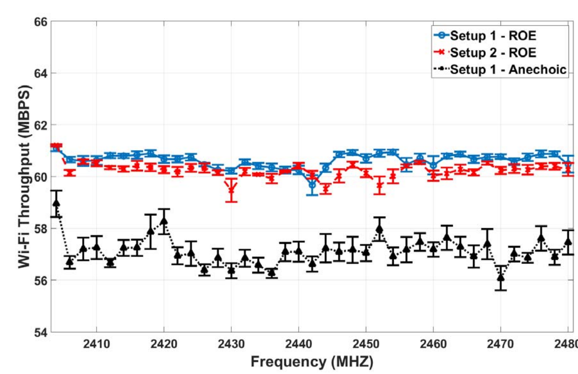

Fig. 9. Frequency test - Average Wi-Fi throughput results.

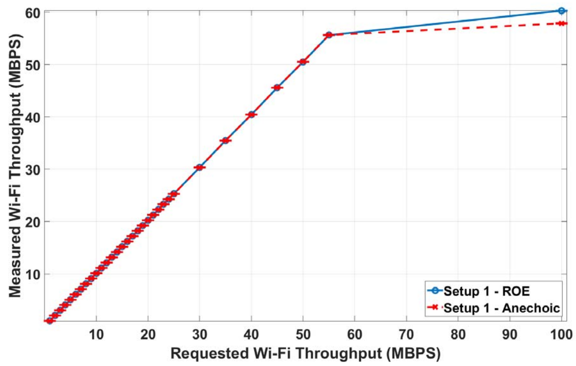

Fig. 10. Throughput test - Average Wi-Fi throughput results.

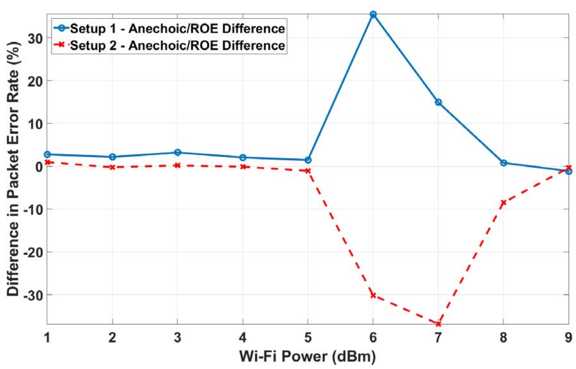

Fig. 11. SIR test - Difference in PER between radiated anechoic setup 1 and ROE setup 1 and between radiated anechoic setup 1 and ROE setup 2.

C. Calculated Difference in Packet Error Rate and Throughput

Figures 11 - 13 shows the differences in PER between ROE and radiated anechoic measurements. By using the anechoic data as a baseline, we can examine the similarity between the different test setups and network layouts.

Figure 14 shows the difference in throughput for the radiated anechoic and ROE tests where we use the radiated anechoic test data as a baseline.

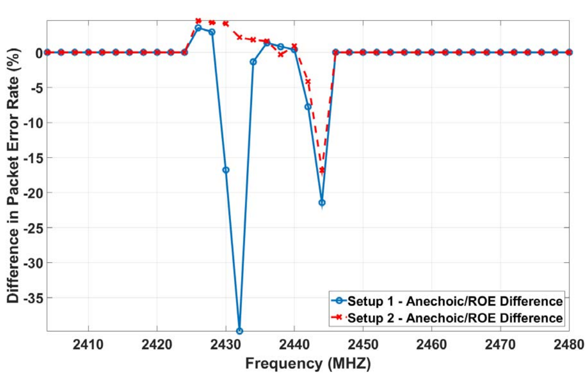

Fig. 12. Frequency test - Difference in PER between radiated anechoic setup 1 and ROE setup 1 and between radiated anechoic setup 1 and ROE setup 2.

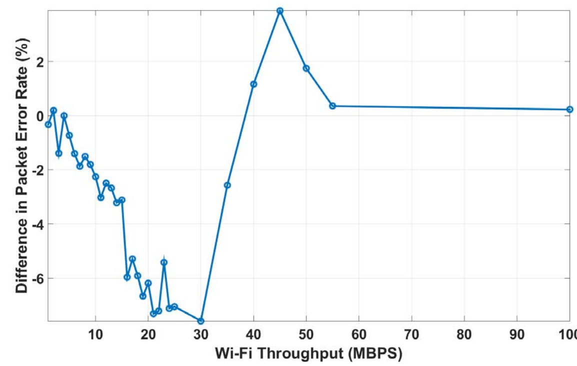

Fig. 13. Throughput test - Difference in PER between radiated anechoic setup 1 and ROE setup 1.

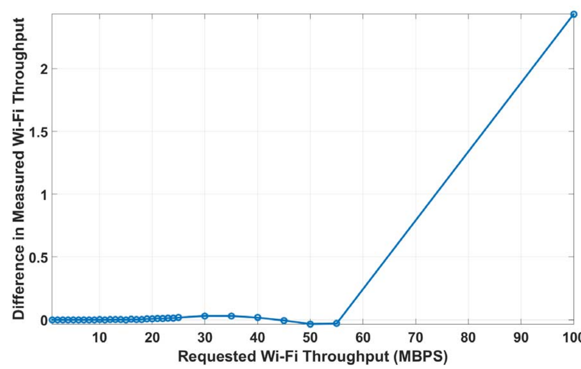

Fig. 14. Throughput test - Difference in measured throughput between radiated anechoic setup 1 and ROE setup 1.

V. Analysis

The PER data from the radiated anechoic and ROE follows the same trend with slight variations between different physical layouts. The variations between the PER results for the SIR test is shown in Figure 11. Recall that the ROE test utilizes two different physical network layouts, thus there is a sign difference with respect to the anechoic measurement. We can calculate this difference by using the anechoic setup as a baseline. Differences in the ROE measurements are visible in Figure 5, as a result of the variation in power received by the DUT. The DUT received power ranged from -58 dBm to -65 dBm due to changes in the separation distance between the DUT transmitter and receiver. Since the DUT received power differs, the PER susceptibility caused by the effects of the unintended network will also vary.

For the frequency test, the PER data between the radiated anechoic and the ROE setup 2 are similar. Here, the DUT is changing its center frequency for each test step. As the DUT enters the same frequency space as the unintended network, the PER goes from 0% to 100%. For ROE setup 1, there is a drop of 40% in the PER. This drop in the PER is most likely due to environmental effects. In the ROE test, the environment is dynamic and may not be precisely the same between the two different network layouts. The difference between the ROE setups is shown in Figure 12.

The throughput test not only compares how close the PER rate is in Figure 13 but also the throughput of the actual test shown in Figure 14. There is a high degree of correlation between the radiated anechoic test and the ROE setup 2. The data indicate the difference between setups is nearly zero, with the exception of the 100 Mbpbs test. This indicates that the environment does not have a significant effect on the measured PER. With throughput between the two different environments being nearly identical the development boards did not lower throughput based on the measured RF environment.

All test runs are LoS between transmitter and receiver. Since all test layouts and test runs are similar, we conclude the layout of the devices does not affect the outcome of the coexistence measurements.

This paper did not examine non-line of sight effects (e.g., multipath). NLoS situations may be used when one desires to replicate the actual deployment environment of a device. In these situations, there may be additional variation between the anechoic and ROE environments. In NLoS conditions the ability to recreate the same multipath conditions will have a significant impact on the ability to reproduce results across environments.

VI. Conclusion

The ANSI C63.27 standard discusses four popular coexistence measurement methods. Here, two methods are examined to investigate what impact the test environment has on the outcome of the test. The test data recorded in different layouts for the different test runs (SIR, throughput, and frequency tests) indicate that the layout of the devices in the network do not have a significant effect on the coexistence measurements when the separation distance between the devices is set as described in Section III (in this case, -60 dBm).

With the DUT transmitters and receivers being in LOS of each other, the coexistence measurements strongly agree between radiated anechoic and ROE. Any physical layout of the devices will yield similar results so long as they have a clear LoS and follow the test procedure. However, each environment is used to test different aspects. Anechoic environments attenuate external RF signals and allow an examination of the coexistence between the DUT and unintended networks. The ROE can be a closer approximation to a real deployment environment. The disadvantage of ROE tests is that they are susceptible to ambient signals not part of the coexistence test.

Future work will examine multiple test layouts in all test environments: conducted, radiated anechoic, ROE, and hybrid. This could also include measurements of the DUT's impact on other devices and testing in NLoS conditions.

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