Dynamic Performance of IEEE 802.15.4 Devices Under Persistent WiFi Traffic

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***Abstract*—Recent studies have provided coexistence and interaction models between IEEE 802.15.4 and IEEE 802.11 standards. However, the performance of IEEE 802.15.4 devices under WiFi interference are evaluated based on limit parameters i.e. Packet Reception Rate, which does not exhibit the dynamic interactions in the wireless channel.**

In this paper, we conduct a series of experiments to demonstrate the dynamic interactions between the IEEE 802.15.4 and IEEE 802.11 bgn standards on relevant devices. The performance of four existing Link Quality Estimators (LQEs) of IEEE 802.15.4 nodes under the IEEE 802.11 bgn interference is analyzed. We show that IEEE 802.15.4 transmission failures are largely due to channel access failures rather than corrupted data packets. Based on the analysis, we propose a new LQE - Packet Reception Rate with Clear Channel Assessment - by merging the Clear Channel Assessment count with the Packet Reception Rate. In comparison to existing LQEs, results show that the new estimator distinguishes persistent IEEE 802.11 bgn traffic more robustly.

Keywords—802.15.4; WiFi; interference; clear channel accessment; coexistence

I. INTRODUCTION

A Wireless Sensor Network (WSN) consists of spatially distributed autonomous devices that cooperatively sense and monitor a physical or environmental condition. WSN plays an intrinsic role as part of the Internet of Things (IoT), reporting environmental information and surrounding context wirelessly to IoT devices, particularly in smart home and building applications.

Approximately 40% of global greenhouse gas emissions and waste can be attributed to buildings [1]. The push to reduce the overall carbon footprint and its impact on the built environment on human health and the ecosystem has seen a steady rise in the number of green buildings. For better conservation, smart electronics such as temperature, humidity and luminance sensing devices can be incorporated into buildings for improved environmental monitoring. Specifically, WSN proves to be an attractive and important enabler for accurate sensing and communication between devices both in terms of associated installation cost as well as the flexibility it offers in sensor placements.

WSN devices using IEEE 802.15.4 standard are known to be low-cost, low-power and low data rate. Nonetheless, they are vulnerable to environmental factors such as long distance [2], RF interference that shares the same ISM band [3, 10, 11, 12] and human activities [9]. WSN optimization protocols design to improve wireless communications are generally implemented using link quality estimation in an environment. Given the ubiquity of wireless technology, accurate Link Quality Estimators (LQEs) are desired for an optimization protocol to execute optimally [4]. Different complications prevailing in the network may impact the network differently and often require different solutions [5]. Failure to identify the source of interference may adversely affect the network's performance.

WiFi (IEEE 802.11 bgn) devices with higher transmission power and higher transmission duty cycles are known to be interference to WSN (IEEE 802.15.4) devices [3, 10, 11, 12] which operate in the same environment and 2.4 GHz ISM band. Random file transfer through WiFi, and wide deployment of WiFi devices make quantifying the performance of IEEE 802.15.4 devices non-trivial [4]. It is therefore crucial to identify WiFi interference and quantify its impact on IEEE 802.15.4 devices. The knowledge of the proximity and impact of an interference will enable WSN optimization protocols to act accordingly, for example, switching channels, defining the right number of retries or CSMA backoff, optimizing transmission duty cycle and increasing transmission power.

Coexistence issues between IEEE 802.15.4 and IEEE 802.11 standards are reported in [3, 10, 11, 12]. The interaction behavior between the two standards boils down to three factors; adequate frequency separation, sufficient distance resulting to an improved Signal to Interference Ratio (SIR), and overall occupancy of the wireless channels [11]. IEEE 802.15.4 is found to impact IEEE 802.11's throughput [3, 12]. In our experiment, we show that this phenomenon dynamically influences IEEE 802.15.4 traffic as well, which is not captured in [10, 12]. Furthermore, the performance of IEEE 802.15.4 devices under WiFi interference are often evaluated based on limit parameters i.e. Packet Reception Rate [3, 10, 11, 12], which in our experiments, we show that it does not exhibit the actual happenings in the wireless channel effectively. Hence we propose the use of Packet Reception Rate with Clear

Channel Assessment to distinguish WiFi interference more robustly.

In this paper, a series of experiments was designed with the objective of evaluating the performance of the IEEE 802.15.4 devices' LQEs under WiFi interference. The reported LQEs are Link Quality Indicator (LQI), Bit Error Rate (BER), Clear Channel Assessment (CCA) count, Packet Reception Rate (PRR) and the newly proposed Packet Reception Rate with Clear Channel Assessment (PRRCCA).

The rest of the paper is organized as follows. A coexistence overview between IEEE 802.15.4 and IEEE 802 bgn devices is introduced in Section II. Configuration of nodes, LQEs to be monitored, and experimental setups are described in Section III. In Section IV, using the design of experiments, we evaluate the LQEs performance of IEEE 802.15.4 devices under the persistent WiFi interference. Finally, we conclude our findings in Section V with proposed future works.

II. Overview of System Coexistence

Data packet collision occurs when there is more than one node transmitting packets in the same channel simultaneously. Wireless networks nodes usually cannot hear their own transmissions, and any colliding data packets can only be detected after completion of a transmission, generally through acknowledgement (ACK). To avoid data packet collisions, Carrier Sense Multiple Access – Collision Avoidance (CSMA/CA) mechanism is implemented as a standard feature for contention resolution in computer networks. However, fair channel access between different standards is not always achievable. This is due to the difference in application requirements and operating procedures i.e. WiFi devices with a much higher transmission power, higher transmission duty cycle and shorter backoff period than IEEE 802.15.4 devices tend to occupy the channel more often.

A. IEEE 802.15.4 standard

IEEE 802.15.4 standard defines the Physical Layer (PHY) and Medium Access Control (MAC) for Low Rate Wireless Personal Area Network (LR-WPAN). In this paper, we focused on operations in the 2.4GHz ISM band. There are a total of 16 channels with each occupying a bandwidth of 5MHz. The maximum output power of the IEEE 802.15.4 radio is typically 0dBm and receiver sensitivities are -85dBm. Transmission ranges up to 100m with a transfer rate of 250kbps.

To reduce the chances of concurrent transmissions between multiple nodes, IEEE 802.15.4 adopts either slotted or un-slotted CSMA/CA. In this paper, only un-slotted CSMA/CA is considered. Before an IEEE 802.15.4 node attempts to transmit, it backs off for a random time to prevent possible synchronization with other nodes. After this initial random backoff, a Clear Channel Assessment (CCA) is performed for eight symbol periods to sense if the channel is busy. If detected to be busy, the backoff process will be repeated the maximum allowed CSMA/CA backoffs. Else if the channel is detected as free, the data packet can be transmitted.

An optional ACK can be requested. In this case, the entire transmission is successful if the data packet originator receives an ACK from the recipient within an allowed MAC ACK waiting period. Else if no ACK is received within that time, the packet will be retransmitted up to a maximum defined MAC retransmissions to ensure communication reliability. If the maximum MAC retransmission is reached, the protocol terminates the data packet and the transmission is considered to have failed.

B. IEEE 802.11 bgn standard

IEEE 802.11 b, IEEE 802.11 g and IEEE 802.11 n standards specify the PHY and MAC for Wireless Local Area Networks (WLAN). IEEE 802.11 standard has been widely adopted in WiFi. They define 13 overlapping 22MHz wide frequency channels in the 2.4GHz ISM band. The different versions of IEEE 802.11 standards are enhancements from the previous version with higher data rate and transmission range. However, they employ the same CSMA/CA mechanism defined in the original IEEE 802.11 standard. The difference in data rate and their typical operating range are shown in Table I.

TABLE I. Comparison of 802.11 WLAN Standards.

WLAN Standard	Maximum data rate (Mbps)	Operating frequency band (GHz)	Approximate indoor range (ft)
IEEE 802.11 b	11	2.4	125
IEEE 802.11 g	54	2.4	125
IEEE 802.11 n	300	2.4 & 5	230

Similar to IEEE 802.15.4, an IEEE 802.11 node is required to sense the channel before initiating a transmission. Sensing of channel determines whether another node is transmitting as well. If the channel is detected idle for Distributed coordination function Inter-Frame Space (DIFS) time, the transmission will proceed. Otherwise, the node will initiate a backoff timer with a randomly chosen interval. The decrement of the backoff timer will happen only when the channel is detected idle for a backoff time slot. The backoff timer will pause when a transmission is detected and resume when the channel is idle again. The node is allowed to transmit only after the backoff timer reaches zero.

III. Experimental Setup

To understand the performance of IEEE 802.15.4 nodes under persistent WiFi interference, two different experimental setups with multiple test conditions are designed and explained in section C and D. For each test condition, the monitored IEEE 802.15.4 nodes and the WiFi source are configured and controlled (section A). Only the device placement was varied to simulate different test conditions. The definition of IEEE 802.15.4 LQEs are also explained in section B.

All experiments are set up using off-the-shelf communication devices and conducted in an office aisle with LOS communication during non-working hours. Sanity checks are performed (section E) to ensure no dominant uncontrolled interference is present in all test conditions.

A. Test nodes configurations and sanity checks

For our experiments, we have used development test boards (JN5168) [6] manufactured by NXP Semiconductors as the IEEE 802.15.4 network. Two IEEE 802.15.4 nodes are configured to exchange data packets of 100 bytes size every 10ms at a data rate of 250kbps on channel 20 (2450MHz). The transmission power is set at 0dBm. Every IEEE 802.15.4 transmission is independent from the previous packet, such that transmission failure due to buffer overflow is avoided [10]. The maximum retransmission and maximum CSMA backoff are set to zero. This is done so that whenever the IEEE 802.15.4 node fails to access the channel while attempting to transmit; the entire transmission process is considered failed. Similarly, if no ACK is received after a data packet is transmitted successfully, the entire transmission process is considered failed. All IEEE 802.15.4 traffics are recorded on Dell Latitude E6330 laptops connected via USB, from which the LQEs are extracted.

WiFi traffic is generated using Linksys Wireless-N Router (WR) (WRT160NL) [7] connected to Dell Latitude E6330 laptops via Ethernet port. Laptops running Iperf [8] generates User Datagram Protocol (UDP) packets of 1500bytes size to a Samsung Galaxy Note II N7100. The WR has a data rate of 130Mbps which varies depending on network conditions and environmental factors. The WR transmit power is capped at 21dBm and is configured to transmit on either channel 9 or 11 to simulate interference frequency offset of 2MHz and 12MHz respectively from IEEE 802.15.4 packets.

A sanity check is performed using an IQ analyzer, Rohde & Schwarz FSV30 and confirms that no dominant uncontrolled interference is present near the IEEE 802.15.4 channel 20. BER and PRR of IEEE 802.15.4 nodes recorded under no WiFi interference are majority 0 and 100% respectively. Here we assumed that any packet failures in the subsequent experiments are caused by the controlled WIFI interference, background noise and multipath effects from the experiment environment.

B. IEEE 802.15.4 Link Quality Estimators

1) Link Quality Indicator (LQI): LQI is determined over the first 4 bytes of a correctly received data packet. It represents the number of chip errors and averaged energy detected over the 4 bytes. In the JN5168 implementation, the LQI of 250 indicates a maximum quality frame and a value of 0 is assigned to the lowest quality.

2) Bit Error Rate (BER): Unlike LQI, BER is extracted from both correctly received and corrupted data packets. BER represents the number of incorrect bits received, when the received data packet is compared to the known frame structure. BER is usually due to noise, interference, or bit synchronization errors. The higher the BER, the poorer the quality of frames.

3) Packet Reception Rate (PRR): PRR in equation (1) is simplified and defined as the success rate for a transmitted data packet to receive an ACK. 100% PRR indicates a perfect reception of all data packets on the destination node. Here, PRR only accounts for packets that are transmitted across the channel and does not account for CCA failure.

$$PRR = 1 - \frac{Number\ of\ transmission\ without\ ACK}{Number\ of\ successful\ CCA\ that\ leads\ to\ transmission} \qquad (1)$$

4) Clear Channel Assessment (CCA) count: +1 CCA count increment relates to a channel access failure (energy detected above a threshold). The number of CCA count relates to the amount of the noise in the transmission channel such that a higher CCA count represents a noisier channel.

5) Packet Reception Rate with Clear Channel Assessment (PRRCCA): We proposed a new LQE, PRRCCA used to distinguish the presence of a persistent WiFi interference (section IV). PRRCCA in equation (2) is defined as the success rate of a CCA resulting in an idle channel and a successful transmission. PRRCCA of 100% indicates a perfectly idle channel and perfect reception of data packet on destination node, while 0% indicates an inaccessible channel caused by a possible overwhelming interference.

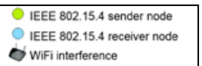
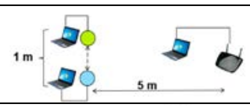
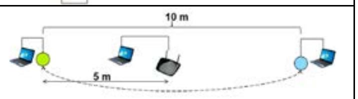
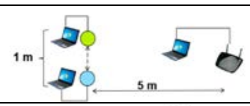
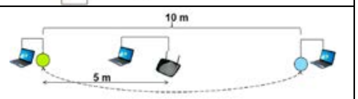
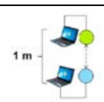
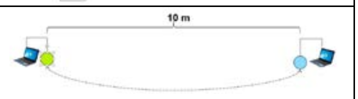
$$PRRCCA = 1 - \frac{Number\ of\ failure\ packets}{Number\ of\ CCA\ attempts}$$

$$PRRCCA = 1 - \frac{Number\ of\ CCA\ failure + Number\ of\ transmission\ without\ ACK}{Number\ of\ CCA\ failure + Number\ of\ successful\ CCA\ that\ leads\ to\ transmission} \qquad (2)$$

C. Experiment setup 1: Operating distance varying IEEE 802.15.4 nodes

Table II illustrates six test conditions, 1A to 1F, categorical into "with or without WiFi interference", "WiFi interference frequency offset", and "IEEE 802.15.4 nodes operating distance". The objective of using different interference frequency offset is to understand if large frequency offsets can truly avoid WiFi interference. To better understand the impact of Signal-to-Interference Ratio (SIR) with varying IEEE 802.15.4 signal strength, different IEEE 802.15.4 nodes operating distance are used such that the receiver node in test condition 1B, 1D and 1F operates with a lower SIR than 1A, 1C and 1E. Note in test conditions 1A to 1D, the WR acting as the WiFi interference is placed 5m away from the IEEE 802.15.4 sender node. Test conditions 1E and 1F are used as reference conditions.

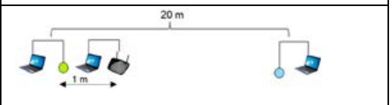
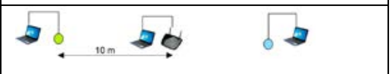
TABLE II. Experiment 1 test conditions.

Test conditions	WR and IEEE 802.15.4 node frequency offset	IEEE 802.15.4 nodes distance apart	Experiment setup 
1A	2 MHz WiFi Channel 9	1 m	
1B	2 MHz WiFi Channel 9	10 m	
1C	12 MHz WiFi Channel 11	1 m	
1D	12 MHz WiFi Channel 11	10 m	
1E	-	1 m	
1F	-	10 m	

D. *Experiment setup 2: Distance varying IEEE 802.15.4 bgn*

Table III illustrates three test conditions, 2A to 2C categorical into the varying distance between WR and IEEE 802.15.4 sender node. For all three test conditions, the operating distance of the IEEE 802.15.4 nodes are kept are 20 m apart, where the WR are placed at 1m, 10m and 19m away from IEEE 802.15.4 sender node. The objective of varying distance of WR is to understand the performance of IEEE 802.15.4 nodes under poor SIR with varying WiFi interference level, and to confirm the reliability of the proposed PRRCCA.

TABLE III. Test conditions for Experiment 2.

Test conditions	WR's distance from IEEE 802.15.4 sender node	Experiment setup	IEEE 802.15.4 sender node; IEEE 802.15.4 receiver node; WiFi interference
2A	1 m		
2B	10 m		
2C	19 m		

IV. Experimental Results and Discussion

A. *Experiment 1: Operating distance varying IEEE 802.15.4 nodes*

Figure 1 shows the LQI performance of IEEE 802.15.4 nodes in test conditions 1A to 1F. Each test condition provides 80 LQI samples of 256 transmissions each. LQI outliers are found in every test condition and are observed to be inconsistent and are the minority among the 80 samples. Note that LQI is based on a correctly received data packet, rather than a corrupted one. Hence, it means that these outliers are correctly decoded data packets with varying chip correlation caused by the background noise and multipath effects from the environment.

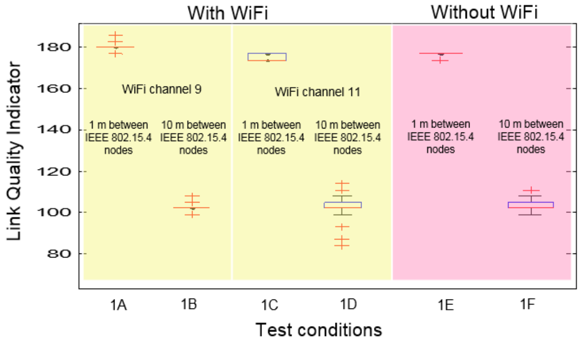


Fig 1. Experiment 1 – Collective LQI of IEEE 802.15.4 nodes under persistent WiFi interference in test conditions 1A to 1F.

It is observed that LQI does not provide a significant difference (P value < 0.05) between test conditions with and without WiFi interference. Instead, LQI varies according to the operating distance between IEEE 802.15.4 nodes only, acting much like a signal strength indicator. For test conditions with 1m and 10m IEEE 802.15.4 nodes operating distance, the LQI are approximately 179 and 102 respectively. The maximum LQI mean difference between test conditions at 1m and 10m are only 3.525 and 1.089 respectively.

Figure 2 shows the BER performance of IEEE 802.15.4 nodes in test conditions 1A to 1F. Note that in test conditions 1A to 1D, the WR is statically deployed such that the channel occupancy for IEEE 802.15.4 sender node is kept constant [12]. It is observed that BER is found only in test condition 1B and 1D. Here, we can say that the packets received by IEEE 802.15.4 receiver node are wrongly decoded, hence the bit errors. The wrongly decoded packets are discarded as illustrate in LQI. In test conditions 1A and 1C where bit errors are not found, IEEE 802.15.4 nodes have a better SIR due to a stronger IEEE 802.15.4 signals at 1m operating distance.

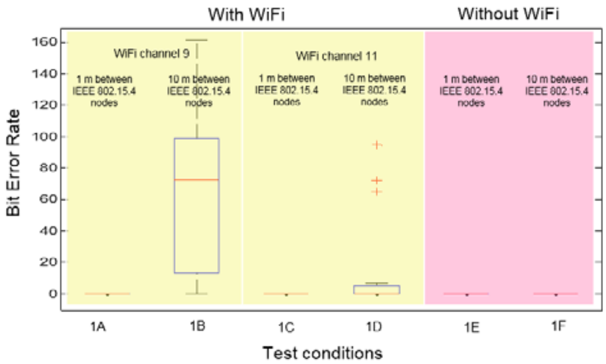


Fig 2. Experiment 1 – Collective BER of IEEE 802.15.4 nodes under persistent WiFi interference in test conditions 1A to 1F.

It is important to note that a successful transmission requires both chip and bit synchronization. Therefore, PRR is a better measurement for the true RF performance.

Table IV shows the results of 20480 transmission attempts for each test conditions 1A to 1F. These transmission attempts can be divided into failed CCA, successful transmission and failed transmission as in equation (3). A successful channel access leads to a data packet transmission, which resulted in either a failed or successful transmission depending if an ACK is received within the maximum MAC ACK waiting period.

$$\begin{aligned} \text{Total TX attempts} &= \text{Total CCA attempts} \\ &= \text{Total failed CCA} + \text{Total successful CCA} \\ &= \text{Total failed CCA} + \text{Total successful TX} + \text{Total failed TX} \end{aligned} \quad (3)$$

Referring to Table IV, it is clear that PRR do not provide a significant indication under the presence of WiFi interference. As expected, the lowest PRR recorded is found in test condition 1B, averaged at only 91.05 %. In test condition 1B, the IEEE 802.15.4 nodes is expected to have the lowest SIR because the WiFi interference operates at only 2MHz frequency offset and nodes are deployed at 10m apart. However, the transmission failures in test conditions 1A, 1C and 1D are found negligible with PRR more than 99.9%. It is observed that the PRR performance directly corresponds to the BER readings where highest BER is found in test condition 1B.

In experiment setup 1, WiFi interference is not reflected in PRR but in the number CCA failures. Majority of the IEEE 802.15.4 transmission failures are due to failed CCA, rather than transmission failure. In test conditions 1E and 1F, where there are no WiFi interference, the CCA failure is negligible. CCA count is observed to be relatively constant in test conditions 1A to 1D due to the static distance between WR and IEEE 802.15.4 sender node. Here, CCA count provides a reliable indicator for WiFi interference.

TABLE IV. Breakdown of 20480 transmission attempts for the experiment setup 1.

Test conditions	1A	1B	1C	1D	1E	1F
PRR %	99.9	91	100	99.9	100	100
Total TX attempts	20480	20480	20480	20480	20480	20480
Total failed CCA	11907	13350	10215	10744	1	1
Total TX	8573	7130	10265	9736	20479	20479
Total failed TX	8	638	0	278	0	0
Total successful TX	8565	6492	10265	9458	20479	20479

Communication robustness between IEEE 802.15.4 nodes is achieved via CSMA/CA mechanism, where a node is denied channel access if the channel is being occupied. By default, the IEEE 802.15.4 standard defines the maximum number of CCA backoff as 4. As a result, PRR in [12] does not reflect the actual channel occupancy since CCA failures do not dominate in PRR calculation. For instance, a node operating in a "noisy" environment may still achieve a relatively good PRR of 99%. However in reality, large amount of battery power are being consumed due to a longer listening operation which is not reflected in the PRR. It is also observed in test conditions 1C and 1D that even with 12MHz interference frequency offset, WiFi interference still influences the IEEE 802.15.4 communication by denying channel access. Again, this phenomenon is not reflected in PRR.

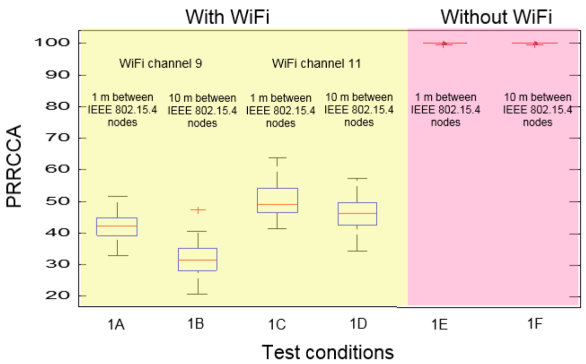


Fig 3. Experiment 1 – Collective PRRCCA of IEEE 802.15.4 nodes under persistent WiFi interference in test conditions 1A to 1F.

Figure 3 shows the PRRCCA performance of IEEE 802.15.4 nodes in test conditions 1A to 1F. It is clear that PRRCCA provides a clearer separation between test conditions with and without WiFi interference. Without WiFi interference, PRRCCA is approximately 100% while under WiFi interference, PRRCCA ranges between 30-50%. Unlike LQI, BER and PRR, PRRCCA provides an indication to WiFi interference presence regardless the interference frequency offset and operating distance between IEEE 802.15.4 nodes.

So far, the WR is kept at 5m distance apart from IEEE 802.15.4 sender node, occupying the wireless channel at a constant rate. To understand the robustness of PRRCCA under varying WiFi interference level, we vary the distance between IEEE 802.15.4 sender node and WR in experiment setup 2.

B. Experiment 2: Distance varying IEEE 802.15.4 bgn

In experiment 2, three test conditions are designed to evaluate the performance of IEEE 802.15.4 nodes under poor SIR with varying WiFi interference level, and to confirm the reliability of the proposed PRRCCA. As shown in Table III, the distance between IEEE 802.15.4 nodes and WR are varied, while the IEEE 802.15.4 nodes operating distance are kept 20 m constantly.

Table V show the breakdown of 17664 transmission attempts for test conditions 2A to 2C. With IEEE 802.15.4 receiver node suffering from a poorer SIR (increased operating distance), PRR provides differentiation among the three test conditions. PRR degrades from 99 % to 28.4 % as WR moves closer to the IEEE 802.15.4 receiver node. In addition, unlike in experiment setup 1, CCA failures here degrades from 3256 to more than 12200. It is observed that when WR approaches IEEE 802.15.4 sender node, the communication performance improves in terms of lesser denial of channel and better transmission reception.

TABLE I. Breakdown of 17664 transmission attempts for experiment setup 2.

Test conditions	2A	2B	2C
PRR %	99	65	28.4
Total TX attempts	17664	17664	17664
Total failed CCA	3256	12202	12765
Total TX	14272	4049	2856
Total failed TX	136	1413	2043
Total successful TX	14136	2636	813

Figure 4 show the PRRCCA performance of IEEE 802.15.4 nodes in test conditions 2A to 2C. Clearly, we see a distinct performance improvement in test condition 2A. This observation can be explain by the impact of the varying distance between IEEE 802.15.4 sender node and WR which results in a dynamic relationship.

In [3], the author identified 3 ranges of operations:

- Range 1 – IEEE 802.15.4 nodes and IEEE 802.11 bg nodes can detect each other
- Range 2 – IEEE 802.15.4 nodes can detect IEEE 802.11 bg nodes but not via versa
- Range 3 – Neither can detect each other well but IEEE 802.15.4 nodes still suffers from IEEE 802.11bg interference

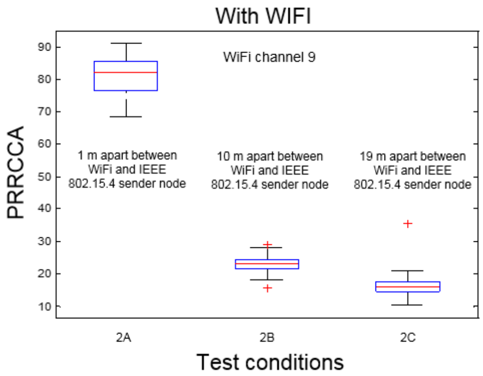


Fig 4. Experiment 2 – Collective PRRCCA of IEEE 802.15.4 nodes under persistent WiFi interference in test conditions 2A to 2C.

In our two experiments setups, the distance between IEEE 802.15.4 sender node and WR are kept below 20m, from which they belong to Range 1 [3] where both devices are capable of detecting each other's traffic. Experiment setup 2 shows that PRRCCA performance degrades as:

- WR approaches IEEE 802.15.4 receiver node
- WR distances from IEEE 802.15.4 sender node

In test condition 2A, WR is capable of detecting IEEE 802.15.4 traffic well and tends to backoff effectively resulting to a WiFi throughput reduction [3, 12]. WiFi throughput reduction dynamically reduces the wireless channel occupancy allowing IEEE 802.15.4 nodes to access the channel more often, leading to more transmitted packet. Transmission are also successful (with ACK) due to the low WiFi interference level on IEEE 802.15.4 receiver node. Hence PRRCCA performs well, indicating a low interference from WIFI traffic.

In test condition 2B, WR still senses IEEE 802.15.4 traffic but not very well due to the low IEEE 802.15.4 transmit power. Here, WiFi does not back off effectively and IEEE 802.15.4 CCA failure starts to dominate. At the same time, as WR approaches IEEE 802.15.4 receiver node, PRR degrades due to a poorer SIR. PRRCCA is therefore intermediate suggesting a presence of WiFi interference.

In test condition 2C, the devices of both standards sense each other's traffic but not very well. Here, WR does not backoff effectively causing a channel saturation inducing both CCA failures and transmission failures on the IEEE 802.15.4 nodes.

V. Conclusion

In conclusion, we have provided a series of experimental evaluations with different layouts to demonstrate that IEEE 802.15.4 and IEEE 802.11 bgn standards dynamically impact each other. Specifically, our findings show that the operating distance between the IEEE 802.15.4 nodes and the interference between the IEEE 802.15.4 nodes and the interference source are key factors affecting the dynamic relationship. We have analyzed the performance of LQEs of IEEE 802.15.4 nodes under the WiFi interference and demonstrated in experiment setup 1 that when IEEE 802.15.4 nodes have a good SIR, transmission failure under persistent interference is largely due to channel access failure rather than corrupted data packets. Hence, we have proposed the use of PRRCCA to identify a persistent interference. The performance of PRRCCA is also further verified in experiment setup 2.

We find that PRRCCA is simple and can potentially provide valuable information about a deployed environment. Since CCA counter is already implemented in the IEEE 802.15.4 hardware system, there is no requirement for additional feature. Unlike LQI and BER, PRRCCA is a sender node LQE which does not require additional information from the receiver node. This will mean a lower requirement for overhead packets.

For future work, we will further validate the applicability of PRRCCA on a real test bed. PRRCCA has the potential to interpret power consumption as it monitors the usage of both receiver and transmitter. More importantly, PRRCCA offers the potential to identify hidden terminal issues, since a hidden terminal induces packet failures on the receiving node but not a CCA failure on the sender node.

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