Testing Time Optimization Method for IEEE 802.15.4z Ultra-wideband Integrated Circuits

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Abstract — IEEE 802.15.4z-compliant ultra-wideband (UWB) devices are becoming ever more popular in contemporary radio engineering systems. Such systems are capable of precisely measuring distances (with their accuracy expressed in centimeters), are immune to interference, offer low latency and transmit data in an energy-efficient manner. Widespread adoption of UWB technology has triggered significant demand for testing integrated circuits these systems rely on, prompting the development of new testing methods to meet the ever increasing requirements in terms of testing speed and reliability. The same applies to sensitivity tests, in the course of which up to 2000 different packets may be received. The process of generating and analyzing such a large number of packets is time consuming. Furthermore, if multiple devices need to be tested simultaneously, the duration of the test will be multiplied accordingly. In such a context, the article investigates the lead time required to generate 2000 UWB packets using conventional methods and proposes a novel approach to significantly reduce packet generation time and improve testing efficiency.

Keywords — interframe spacing, packet generation, RF circuit testing, sensitivity measurements, test time reduction, UWB

1. Introduction

IEEE 802.15.4z UWB systems are short-range wireless communication solutions operating within the frequency range of 3.1 to 10.6 GHz. These systems rely on extremely low radiation power levels which are limited, under FCC regulations [1], to –41.3 dBm/MHz. Such a low spectral power allows UWB systems to coexist with narrowband type signal systems, minimizing potential interference. This advantage allows to take advantage of UWB devices' precise centimeter-level distance determination capabilities in environments in which Wi-Fi and other wireless solutions are used [2].

UWB devices determine distance through the measurement of time of flight (ToF). ToF detection can be achieved through such methods as single-sided two-way ranging or double-sided two-way-ranging, relying on packet exchange between two devices. The first device sends a packet containing a marker. By receiving the packet and detecting the position of the marker, the second device can determine the propagation time of the electromagnetic wave by measuring the time difference between the sent and received markers [3].

As UWB devices are required to be able to receive packets under different circumstances, their sensitivity needs to be measured. Receiver sensitivity is a parameter that describes the lowest power level at which the receiver can detect a UWB signal. In order to measure sensitivity of a receiver a test system is required to generate the necessary packets.

Therefore, in order to be able to reliably determine the sensitivity of UWB integrated circuits (IC), the test equipment should be able to generate 2000 different UWB data packets [4]. The device under test (DUT) receives these packets and assesses the sensitivity level based on the packet error rate (PER). If PER is lower than 1%, the test is considered passed [5]. Generating such a large number of packets will increase the time required for testing a single device.

Additionally, in scenarios involving multiple DUTs undergoing validation, verification or production test phases, the overall test duration multiplies accordingly. Thus, measures should be taken to reduce the time required to generate a large number of packets.

This paper proposes a novel method that greatly reduces the time required for generating a large number of packets by leveraging the National Instruments PXIe-5831 vector signal transceiver (VST) and utilizing script mode software capabilities.

The article is organized as follows. In Section 2, conventional methods currently used to generate the required waveforms are discussed. Thereafter, the algorithm of the proposed method aiming to reduce the waveform generation lead time is presented. In Section 3, PXIe-5831 VST is utilized to generate and receive waveforms using both the conventional approach and the proposed method, with the waveform generation lead time typical of each method being measured and compared. Conclusions are given in Section 4.

2. Waveform Generation Techniques

Four different UWB packet configuration types have been defined in the IEEE 802.15.4z standard. The main characteristics of UWB packets include the following: synchronization (SYNC), start of frame delimiter (SFD), physical layer header (PHR), physical layer (PHY) payload, and scrambled

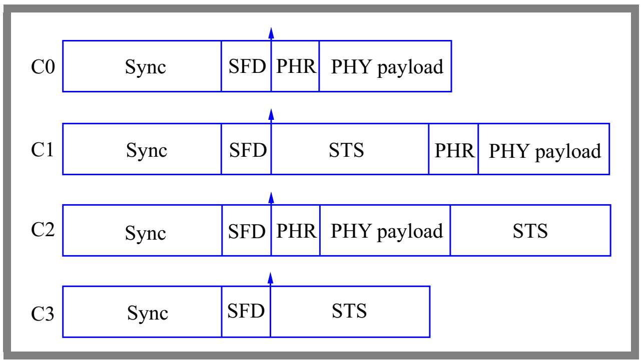

Fig. 1. UWB packet configurations.

timestamp sequence (STS). All of them are shown in Fig. 1. Configuration 0 (C0) does not include an STS inside the packet. In C1 and C2, only the STS location within the frame is changed, while C3 does not include PHR and PHY payload fields. In each configuration, the position of the ranging marker (RMARKER) [6] is indicated by an arrow.

2.1. Iterative Waveform Configuration and Generation Approach

To transmit such packets, the generator should support arbitrary or IQ waveform generation functionality. Typically, these instruments have the ability to save waveforms in their memory and then send them to the digital-to-analog converter (DAC) [7]. Exploiting this capability, one of the conventional methods used to generate a large number of UWB packets relies on creating a packet and downloading it into the built-in memory of a signal generator (SG) [8]. Then the SG generates the packet, repeating these steps in a loop until the required number of packets has been transmitted (Fig. 2).

The advantage of this method lies in minimal usage of SG resources, since an individual packet does not require a significant amount of memory. However, the method involves a time-consuming process of creating waveforms and writing them sequentially into the memory.

To cope with deterministic time intervals between the packets generated it is necessary to allow the receiver to process each frame before the arrival of the next frame. The waveform creation lead time for this method is considered to be idle time.

Nevertheless, because of its non-deterministic behavior, jitter exists in the interframe spacing between the generated packets. The other disadvantage of this method is that waveforms are not saved in the memory. Therefore, whenever it is necessary to generate the same waveforms to test different DUTs, the process of creating waveforms must be repeated, thereby increasing waveform generation lead time.

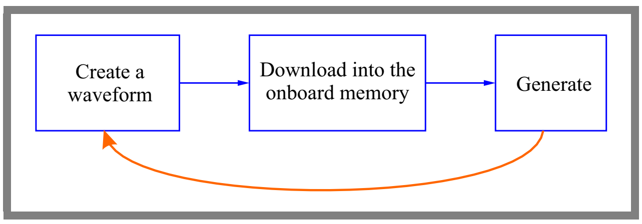

Fig. 2. Iterative waveform configuration and generation approach.

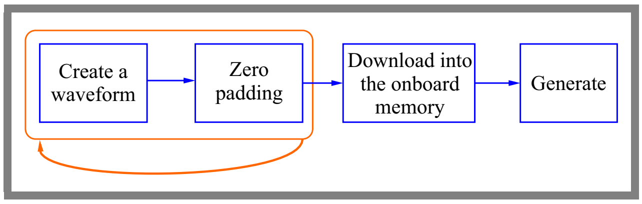

Fig. 3. Zero padding waveform generation approach.

2.2. Zero Padding Waveform Generation Approach

Another conventional waveform generation method addressing these disadvantages involves creating all the required waveforms by adding dummy samples (zeros) after each packet. These zeros do not contain any information and have no power, effectively representing the absence of a signal [9]. The number of zeros determines the interframe spacing time. Once multiple waveforms containing zeros are created, those can be downloaded into the onboard memory of SG, which then generates the entire waveform (Fig. 3).

This approach offers the possibility to define a deterministic interframe spacing time between the packets. However, it results in significant memory usage, as all packets and zeros are downloaded into the onboard memory at once. The equation for calculating the number of waveforms that can be downloaded into the onboard memory is:

$$N_W = \frac{M_{SG}}{M_{SP} + M_0}\,, \tag{1}$$

where N_W represents the number of waveforms, M_{SG} indicates the size of the onboard memory of SG, M_{SP} refers to the memory size of a single UWB packet, while M_0 represents the memory size of padded zeros.

In order to determine the $M_{SP} + M_0$ size, the number of samples N_s used to create the waveform should be considered:

$$N_s = t_w \cdot SR\,, \tag{2}$$

where t_w represents the length of the waveform and SR is the sample rate of SG. This article utilizes the PXIe-5831 with the maximum sample rate of 1.25 GS/s. t_w may vary depending on packet configuration. A UWB signal with the C2 packet format and a length of approximately 150 µs (Fig. 4) was created in the LabVIEW environment. The created packet, illustrated in Fig. 4, was used during the signal generation process.

1 ms interframe spacing is used to allow the receiving device to process each frame before the arrival of the next. With a 150 µs packet, the total length for one waveform would be 1.15 ms. As for numerator of Eq. (1), the typical value for M_{SG} is 2 GB. It may be applied in this scenario as well, as PXIe-5831 has an onboard memory of 2 GB [10]. These values are applied to Eq. (1):

$$N_W = \frac{2\ \text{GB}}{1.15\ \text{ms} \cdot 1.25\ \text{GS/s} \cdot 4} = \frac{2\ \text{GB}}{0.00575\ \text{GB}} = 347.8\,, \tag{3}$$

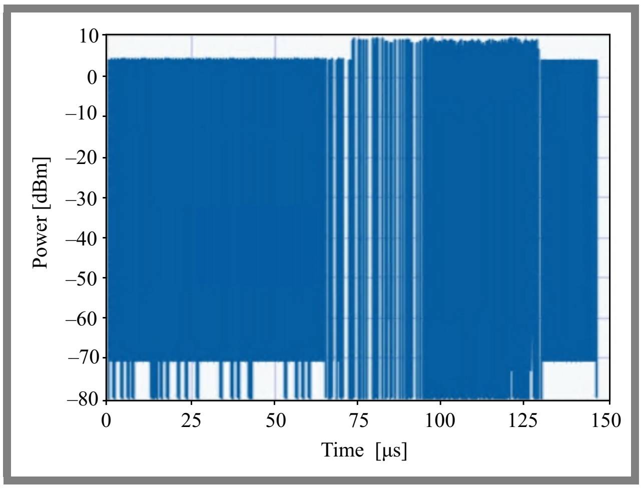

Fig. 4. Generated UWB packet with a length of approximately 150 µs.

where the coefficient of 4 used in the denominator represents the amount of memory allocated to each sample, as the I and Q DACs of the PXIe-5831 have the resolution of 16-bits, i.e. 2 bytes per DAC.

Equation (3) shows that the maximum number of waveforms that can be downloaded into the memory at once is limited to 347 only. This limitation indicates that whenever a greater number of waveforms is re required, this method cannot be utilized.

2.3. Memory-Efficient Interframe Spacing Waveform Generation Approach

The proposed method aims to address the limitations of the previous two approaches. It is similar to the approach shown in Fig. 3. However, instead of adding zeroes to define interframe spacing, a specified number of samples that do not consume memory and effectively represent the absence of a signal is generated.

An algorithm is proposed to generate such multiple waveforms downloaded into the onboard memory in a desired sequence. Between these waveforms, the number of samples required to properly represent the interframe spacing length is defined. An internal, highly deterministic counter algorithm is implemented in LabVIEW to precisely define the length of interframe spacing without memory allocation. The concept relies on integrating a delay function into the SG and counting every generated sample of the instrument. PXIe-5831 offers a maximum sample rate of 1.25 GS/s. Therefore, the minimum possible delay sample will be 0.8 ns, ensuring sufficient interframe spacing accuracy. To represent a 1 ms interframe spacing, the next packet should be delayed by 1 250 000 samples.

Figure 5 illustrates a single waveform, including the packet shown in Fig. 4, and 1 250 000 additional samples to represent 1 ms interframe spacing without consuming the onboard memory.

In this approach, zeros are not used to represent interframe spacing. Therefore, the number of waveforms that can be downloaded into the onboard memory is:

$$N_W = \frac{M_{SG}}{M_{SP}} = \frac{2\ \text{GB}}{0.15\ \text{ms} \cdot 1.25\ \text{GS/s} \cdot 4} = \frac{2\ \text{GB}}{0.00075\ \text{GB}} = 2666.6\ , \tag{4}$$

Equation (4) shows that up to 2666 waveforms can be stored in the instrument's onboard memory at once, effectively surpassing earlier limitation. This represents a significant improvement compared to the zero padding approach, where only 347 waveforms could be accommodated.

3. Results and Analysis

The PXIe-5831 vector signal transceiver is used to generate 2000 packets and to assess the two methods described in Section 2. Initially, the iterative waveform configuration and generation approach is tested, followed by an evaluation of the proposed memory-efficient interframe spacing waveform generation method. A comparative analysis of these methods is performed.

Figure 6 illustrates the test system used, with the PXIe-5831 instrument mounted inside the chassis together with the PXIe-8881 controller. PXIe-5831's generation port is connected to the analyzer port to evaluate the generated waveforms [11].

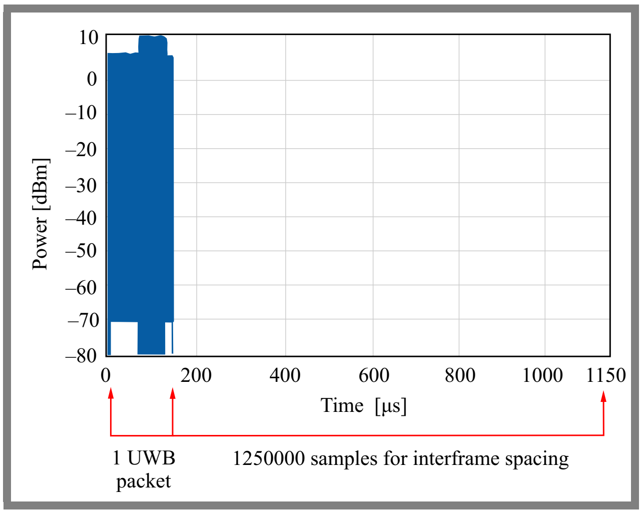

Fig. 5. Generated UWB packet and interframe spacing samples.

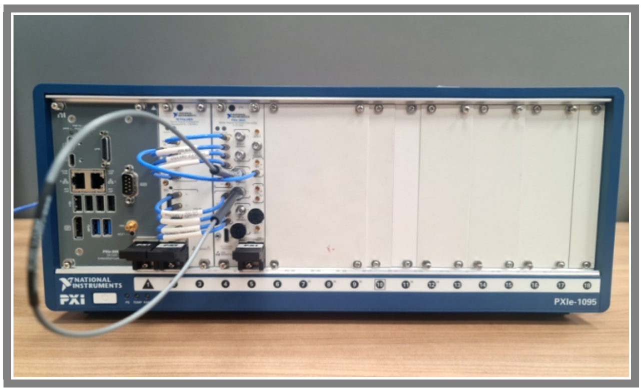

Fig. 6. Test system overview.

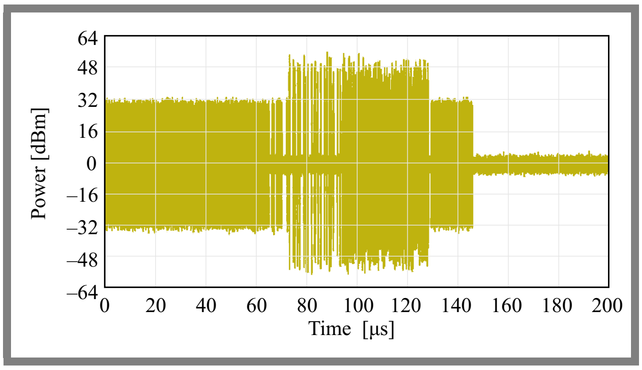

Fig. 7. First packet captured with the use of the iterative waveform configuration and generation approach.

2000 waveforms are used for both methods. The only parameter changed for each waveform is the payload information, which does not modify the waveform length, ensuring validity of the analysis. The algorithm for waveform generation is implemented in LabVIEW using the following UWB PHY parameters [12]:

- mean PRF = 62.4 MHz,
- PHR rate = 0.85 Mb/s,
- data rate = 6.81 Mb/s,
- packet configuration = SP2,
- code index = 9,
- preamble symbol repetitions = 64,
- symbols in SFD = 8.

UWB channel 9 with a carrier frequency of 7987.2 MHz [13] is used for measurements. The signal power level is configured to –10 dBm. The analyzer portion of the PXIe-5831 is configured to capture waveforms based on IQ power level, with a trigger level of –20 dBm.

3.1. Iterative Waveform Configuration – Performance Evaluation

To determine the time required for generating 2000 waveforms with this approach, two timestamps are captured: the first at the start of the initial packet configuration process, and the other after generation of the 2000th packet has been completed. The first captured packet with a length of approximately 150 µs is shown in Fig. 7.

Although interframe spacing was set to 1 ms, the subsequent waveform cannot be observed within this period due to the configuration process. This takes approximately 480 ms and its duration is unstable, adding uncertainty to the interframe spacing length. This duration is measured by recording timestamps at the start and completion of the waveform configuration process. Figure 8 shows, in a histogram, the Gaussian distribution of configuration times measured for each generated waveform, with a standard deviation of $\sigma = 0.01$ and a mean value of 0.48 s.

To assess the generation lead time required on multiple occasions, which is essential for multi-DUT testing, the mathematical representation of generating 2000 waveforms will be:

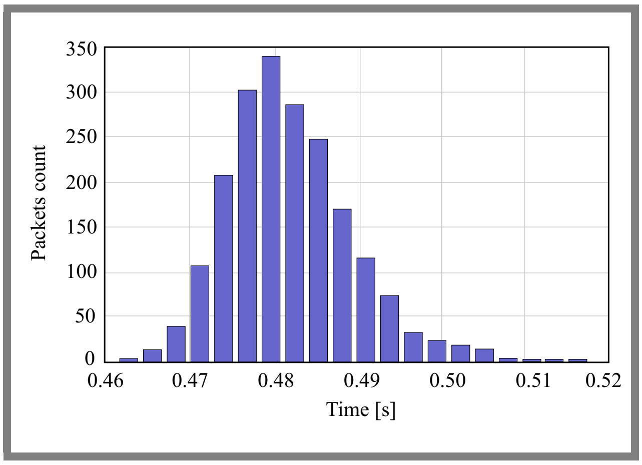

Fig. 8. Gaussian distribution of 2000 configuration times measured.

$$T = N \cdot 2000 \cdot \left[t_{cfg}(\sigma_{cfg} = 0.01) + t_{gen}(\sigma_{gen} \approx 0)\right] , \quad (5)$$

where N represents the number of DUTs to be tested, t_{cfg} is the waveform configuration time, t_{gen} is the packet generation time, and T is the total generation time for N DUTs.

The standard deviation for the total generation time σ_T depends on the standard deviation of the configuration time σ_{cfg}, as the packet generation time is deterministic ($\sigma_{gen} \approx 0$). Assuming that 100 DUTs need to be tested, the total time required for the waveform generation phase is:

$$T = 100 \cdot 2000 \cdot (480 \text{ ms} + 1.15 \text{ ms}) = 96230 \text{ s} . \quad (6)$$

As $\sigma_T = \sigma_{cfg}$ from Eq. (5), 96230 s ≈ 26.73 h and will vary by ±0.27 h.

While this method successfully generates 2000 waveforms, it suffers from a drawback consisting in its inability to accurately define interframe spacing. Additionally, regenerating the same 2000 waveforms requires that they be configured again, as the waveforms are not stored in the instrument's onboard memory. Consequently, the process of generating these 2000 waveforms 100 times would take over 26 hours. It is obvious that the zero padding waveform generation approach, where only 347 waveforms can fit into the onboard memory, will suffer from the same drawbacks.

3.2. Memory-Efficient Interframe Spacing Waveform – Performance Evaluation

This method focuses on two key phases of the process: configuration and generation. Since all the waveforms can be saved in SG's onboard memory, configuration is required only once. Thereafter, the waveforms may be generated as needed. Consequently, in multi-DUT testing scenarios, the 2000 waveforms need to be configured once only. To determine the time required for configuring 2000 waveforms (UWB packets with interframe spacing samples), timestamps are recorded at the start of the process of configuring the first packet and at the end of the process of configuring the last (2000th) packet. The difference between these timestamps represents the time required for the configuration phase. To calculate the gen-

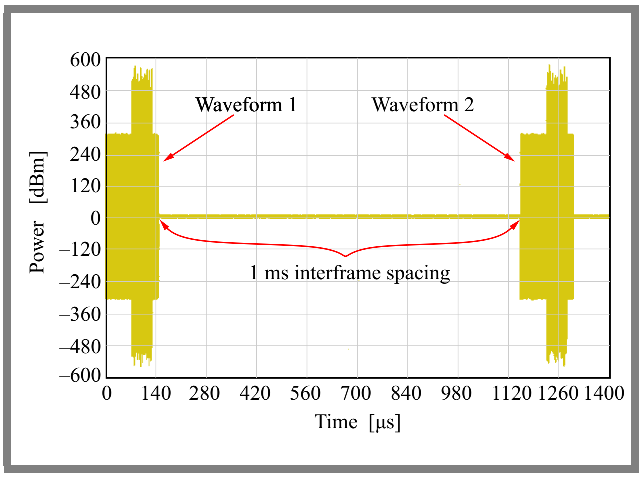

Fig. 9. Time between two subsequent waveforms captured with the use of the memory-efficient interframe spacing waveform generation approach.

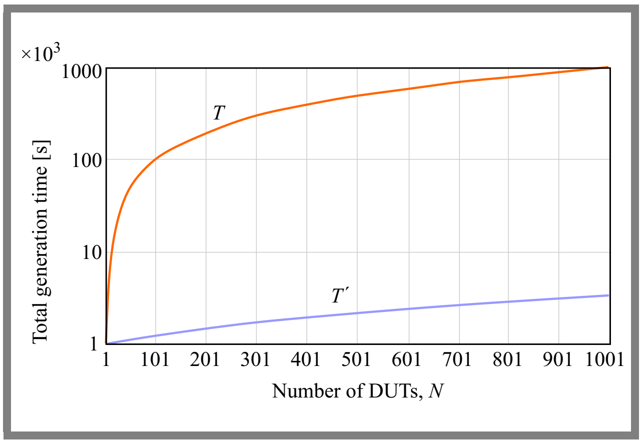

Fig. 10. Relationship between T and T'.

eration time, two timestamps are captured at the end of the configuration phase and after completing the generation of the last (2000th) packet.

The first and the second waveforms captured are illustrated in Fig. 9, showing that the second waveform appears within the next 1 ms, which represents the defined interframe spacing length. Unlike other methods, this approach does not involve a configuration step between the generated waveforms. Therefore, by adding delay samples between the packets, it becomes possible to define the interframe spacing with nanosecond accuracy.

As the waveform configuration phase takes place only once, Eq. (5) should be modified as follows:

$$T' = 2000 \cdot \left[t_{cfg(\sigma_{cfg}=0.01)} + N \cdot t_{gen(\sigma_{gen}\approx 0)}\right] . \tag{7}$$

Assuming that the same number of 100 DUTs needs to be tested, the total time required for the waveform generation is:

$$T' = 2000 \cdot \left[480 \text{ ms} + 100 \cdot 1.15 \text{ ms}\right] = 1190 \text{ s} . \tag{8}$$

As $\sigma_T = \sigma_{cfg}$ from Eq. (7), 1190 s $\approx$ 0.33 h and will vary by ±0.003 h.

From Eqs. (6) and (8) it is clear that $T' \ll T$, showing that the proposed method optimizes the time required for generation large numbers of packets. Furthermore, the difference between T and T' increases when the number of tested DUTs goes up, as illustrated in Fig. 10.

4. Conclusion

An investigation of test time optimization techniques for IEEE 802.15.4z UWB devices was performed, focusing on measurements requiring a large number of packet generations. Conventional UWB packet generation methods were analyzed, exhibiting such drawbacks as time-consuming waveform configuration processes, difficulties with accurate definition of interframe spacing, and significant memory requirements.

To address these challenges, a novel memory-efficient generation technique was proposed. This method utilizes a specified number of delay samples between packets to define interframe spacing, eliminating the need for zero padding. This has been achieved by integrating a delay function into the signal generator, thus allowing to define the interframe spacing with an accuracy of 0.8 ns.

By leveraging National Instruments PXIe-5831 VST and LabVIEW software environment, an algorithm has been implemented showcasing significant improvements in waveform generation time and memory utilization. Calculations demonstrated that it is feasible to store up to 2666 UWB packets in the generator's onboard memory, which is a significant improvement compared to the conventional approaches, where only 347 packets could be stored. Also, the waveform generation lead time has been drastically reduced to 0.33 hours, compared to 26.73 hours when testing 100 DUTs. Experimental results confirmed that the proposed method offers the flexibility of configuring 2000 waveforms only once, making it highly suitable for multi-DUT testing scenarios.

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