

Z-Stack Duty Cycle Analysis

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Keywords

- *Z-Stack*
- *ZigBee, IEEE 802.15.4*
- *FCC*
- *ETSI, ARIB*
- *TransmitApp*
- *Duty Cycle*
- *CC2530, CC2520*
- *CC2590, CC2591*

1 Introduction

Z-Stack is a fully ZigBee-compliant stack running on top of IEEE 802.15.4-compliant TI LPRF SoC/Transceiver and TIMAC.

ZigBee-supporting TI LPRF devices like CC2530 and CC2520 provide wide communication range with their excellent 102-dB link budget and robustness with their best-in-class selectivity performance. However, depending on the condition and the purpose of the application, there can be some necessity to extend the range or improve the robustness by increasing TX power adding RF frontend like CC2590 and CC2591 that provide up to 14 dBm and 22 dBm respectively. In this case, concern about TX power and spurious emissions exceeding limits defined by regulatory standards may arise from peak value point of view.

ZigBee standard based on IEEE 802.15.4 was developed basically considering intermittent data transmission and ZigBee applications are typically designed as such. Therefore, the average values of TX power and spurious emissions, which are calculated from the duty cycle, in ZigBee applications are likely to be significantly lower than the peak values.

This application note describes duty cycle requirements, as defined by the FCC Title 47 CFR Part 15 [1]. However, this document is applicable to ARIB STD T-66 as mean power measurement is used in its specification. Also, the concept of duty cycle described in this document is helpful to prepare for ETSI EN 300 328 even though how to apply duty cycle to the measurement is defined in different way in its specification.

We present theoretical and empirical analysis of the ZigBee-compliant Z-Stack running the TransmitApp application.

TransmitApp is an application utility for establishing a connection between a sender and receiver and transmitting application payloads at the fastest rate allowable by the system [7]. We utilize TransmitApp in our duty cycle analysis to maximize communication and therefore maximize on-air (TX) time in which the sender has control of the channel in order to understand the maximum affect on duty cycle an application can have.

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2 Abbreviations

ACK	Acknowledgement
APS	Application Support Sublayer
ARIB	Association of Radio Industries and Businesses
CFR	Code of Federal Regulations
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific, Medical
LPRF	Low Power RF
MAC	Media Access Control
NWK	Network
PHR	PHY Header
PIB	PHY Information Base
PSDU	PHY Service Data Unit
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
RX	Reception
SFD	Start-of-Frame Delimiter
SHR	Synchronization Header
SoC	System on Chip
TX	Transmission
ZDO	ZigBee Device Object

3 Regulatory Requirements

3.1 FCC Standard Overview

In the United States, FCC is responsible for the regulation of all RF devices. Since CFR 47 Part 15 [1] regulates RF products intended for unlicensed operation, products in that category are subject to compliance testing. If a product is approved, FCC will issue an identification number.

Unlicensed radio equipments for 2.4GHz band are regulated by sections 15.247 and 15.249. General rules for certification measurements are found in section 15.35. Restricted bands and general limits for spurious emissions are found in sections 15.205 and 15.209 [5].

For frequencies above 1 GHz, the radiated emission limits are based on average measurement by FCC section 15.35. However, there also is a limit on the peak level of the radio frequency emissions. The peak limit is 20 dB above the specified average limit [1].

3.2 Duty Cycle

Duty cycle is used to reduce the value measured with an average detector. ZigBee devices typically have low duty-cycle TX operations. This makes average radiated emission lower and consequently enables the device to use higher output power with respect to regulations.

The average value is determined by averaging absolute voltage of the pulse train for any 100 ms interval during which the field strength is at its maximum [1]. The duty cycle is defined as the total "TX time" divided by the 100 ms period. The duty cycle correction factor or the pulse desensitization factor δ can be expressed, in terms of dB, as:

$$\delta = 20 \log_{10} (\text{Duty Cycle})$$

Therefore a 50 % duty cycle will allow 6 dB higher peak emission than without duty cycling and 10 % duty cycle will allow 20 dB higher for example.

4 Analyzing Duty Cycle

For a ZigBee device, the TX duty cycle, is a result of over-the-air transmissions that can be triggered by one or more applications residing on the device, in addition to general communication that is the result of ZigBee management, routing, MAC layer communication, or other components of the ZigBee stack. Because there are many levels of complexity to a device operating within a ZigBee ad-hoc mesh network, it is impractical to analyze all scenarios, traffic conditions, and causes of communication that determine the duty cycle of a member of the network ecosystem. Fortunately when looking at the various contributors to duty cycle for any given device it is apparent that application throughput is the dominant determinant of duty cycle and therefore can be analyzed independently of these other contributors. This assumption can be made safely since:

- Broadcast traffic initiated by the application or network layers contributes significantly less to duty cycle than application unicast traffic since rebroadcasting and artificial delays imposed by the stack require a large percentage of time for a device spent in idle or receive mode. The delays specified in ZigBee specification [3], where *nwkMaxBroadcastRetries*, *nwkPassiveAcktimeout*, and *nwkcMaxBroadcastJitter* are defined, are applied as following.
 - o The broadcast originator typically retransmits the same frame up to *nwkMaxBroadcastRetries* times and there is a delay up to *nwkPassiveAcktimeout* depending on conditions, between retransmissions.
 - o The repeaters also shall have some delay up to *nwkcMaxBroadcastJitter* before relaying the received broadcast frame.

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- Routing of network wide communication in general will contribute significantly less to duty cycle than application throughput can since routing activity involves the receiving and forwarding of messages, with surrounding nodes continuing the forwarding effort and therefore any node participating in routing will spend significant time with the transceiver off or in RX mode that do not contribute to duty cycle while packet forwarding occurs at surrounding nodes. In general for routing:
 - o When forwarding a routing packet there is approximately 5 ms processing delay per packet. This could be more if security is considered, but for the purposes of this discussion we will leave security out as it would add to processing delay and therefore reduce duty cycle. When considering the process of receiving a maximum size packet (4.256 ms), a *TurnaroundTime* (192 us) [3], 352 us ACK transmission time, a MAC CSMA/CA delay of 1.12 ms before re-transmission, and a 4.256 ms packet transmission time, we are looking at a duty cycle of around 30 %.
$$\text{Duty Cycle} = \frac{4.256 + 0.352}{4.256 + 0.192 + 0.352 + 5 + 1.12 + 4.256} = 30.4 \%$$
$$\delta = 20 \log_{10} 0.304 = -10.34 \text{ dB}$$
 - o When performing route establishment or route maintenance, the contribution to duty cycle will be significantly less. When a device must route a packet to another node in the network and no up-to-date route exists, the device will transmit a route request packet. This route request packet is retransmitted by each device in the network and is accompanied by large (20-50 ms) delays to buffer time for neighbouring devices to retransmit without interference. As a result, there will be significant time spent by a given node in RX mode while neighbouring nodes transmit and retransmit this broadcast. Any specific node will therefore spend a significant majority of its time during this operation in RX and would communicate at most two route request packets in a 100 ms window. During this operation a node may also send a route response packet as part of the route establishment procedure, contributing a total of 3 packets in any given 100 ms window. With packet size around 50 bytes taking less than 4 ms to transmit, assuming the contribution of route maintenance to duty cycle would be less than 10-15 %.
 - o Overall we can therefore assume that when routing operation dominates the utilization of a device's transceiver, assuming the worst case duty cycle will still remain less than 30 %.
- Additional messaging and communication to and from a device that will affect duty cycle include network management such as startup, network formation and discovery, joining and address assignment, binding, security management, network management, ZDO management, and inter-pan communication are all relatively infrequent low duty cycle operations, and can be ignored for the purposes of this application note.
- Application throughput, defined as communication initiated by the application layer of a device, often results in one-way communication that can take place without delay and under worst-case conditions will serve to maximize utilization of the transceiver and, therefore, will be the dominant contributor to duty cycle. Therefore, consider the effects of application throughput independent of broadcast or network layer (routing) communication in the next section to fully understand the worst case duty cycle of a device.

5 Worst Case Application Duty Cycle Scenario

For this application note, analyze and test empirically and theoretically the worst case scenarios for packet transmission as it pertains to maximizing duty cycle within the constraints of the ZigBee protocol specification [2]. Use maximum packet / payload length in the analysis to maximize the on-air (TX) time during operation.

The maximum payload size for an application is based on several factors. The MAC layer provides a maximum payload length of 116 (can be changed in f8wConfig.cfg – MAC_MAX_FRAME_SIZE [6]). The NWK layer requires a fixed header size, one size with security and one without. The APS layer has a variable header size based on a variety of settings, including the ZigBee Protocol Version, APS frame control settings, etc... The overall maximum message sent by a device is 133 bytes including 4-byte Preamble, 1-byte SFD, 1-byte Length, and maximum 127-byte PSDU fields as shown in Figure 1.

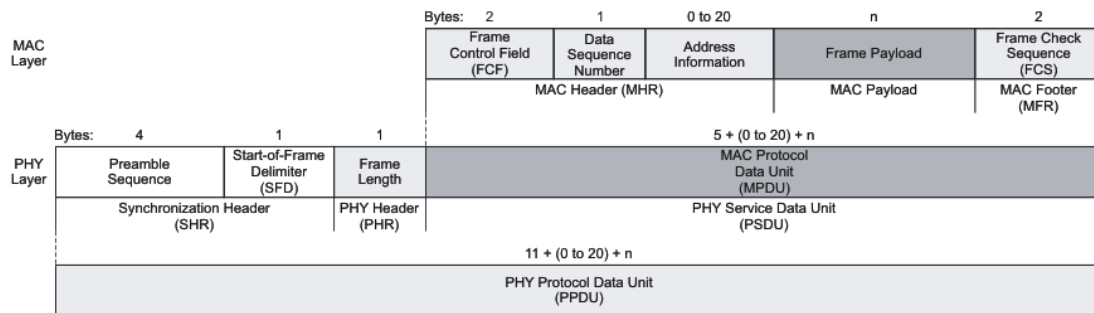


Figure 1. Schematic View of the IEEE 802.15.4 Frame Format [4]

Measure on-air (TX) duty cycle for two cases:

Case 1: Sending a maximum length data frame with ACK requested and ACK received

Consider the case where the ACK is received successfully for every communication as this reflects the quickest response turnaround that will result in a minimum delay before a subsequent communication takes place. This does not necessarily reflect the highest duty cycle scenario, and in fact results in a lower duty cycle than case 2. However, include both cases for completeness to cover the boundary scenarios.

Case 2: Sending a maximum length data frame with ACK requested and ACK missed

Consider the case where the ACK is completely missed for every communication as this reflects the alternate extreme, where ACK wait time is followed by a subsequent packet transmission attempt. This case (case 2) results in the higher duty cycle scenario.

Only consider acknowledged communication cases since unacknowledged communication which is likely to be broadcast transmission has considerably low duty cycle as we reviewed in Chapter 4. Both cases are presented in detail with analysis below.

5.1 Case 1: Maximum Length Frame with ACK Received

Calculate the theoretical and empirical duty cycle for a maximum length frame sent with acknowledgement requested and acknowledgement received 100% of the time.

5.1.1 Theoretical Analysis

$T_{\text{Long Data Frame}}$ is the total on-air (TX) time for sending the data frame (referred to below as the *long data frame*). The long data frame consists of 6 bytes of SHR/PHR and 127 bytes of

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PSDU (or 133 bytes total packet size). It takes 4.256 ms (or 133 bytes x 32 μ s/byte) to transmit the maximum length data frame.

T_{ACK} is the time to wait for the ACK response to the long data frame. T_{ACK} is defined by IEEE 802.15.4 specification [2] as:

$$aTurnaroundTime \leq T_{ACK} \leq (aTurnaroundTime + aUnitBackoffPeriod), \text{ or} \\ 192 \mu\text{s} \leq T_{ACK} \leq 512 \mu\text{s}$$

However, the sender CC253X generally needs to wait only 192 μ s for an ACK because the receiver CC253X running TIMAC / Z-Stack has exactly an *aTurnaroundTime* of 192 μ s before sending the ACK response. T_{ACK} in this case is 192 μ s.

T_{RX_ACK} is the time spent receiving the ACK frame. The ACK frame consists of 6 bytes of SHR/PHR and 5 bytes of PSDU (or 11 total bytes). It takes 352 μ s (or 11 bytes x 32 μ s/byte) to receive the ACK frame.

$T_{Process}$ is the processing time from the point of receiving the ACK to restarting the process of transmitting another data frame. For the CC253X, the processing time from the point of receiving an ACK frame to readying the stack to transmit another data frame is empirically determined to average 2.2 ms. This time period includes the RX to TX turnaround time (*aTurnaroundTime*) of 192 μ s and RSSI sampling time for CSMA/CA of 128 μ s. This assumes that there is no other traffic in the channel that causes CSMA/CA to fail.

$T_{Ave\ Backoff}$, as defined by the IEEE 802.15.4 protocol specification, is a randomized backoff period required prior to the transmission of any data frame to ensure fair channel access in such a distributed network. The backoff period is a random number from 0 to 7 applied on the first TX attempt of a data frame. The average backoff period across many packet transmission is therefore 1.12 ms (or 3.5 backoffs x 320 μ s / backoff).

$T_{On\ Time}$ is the time to transmit the long data frame or 4.256 ms. This is the on-air TX time that contributes directly to duty cycle.

$T_{Off\ Time}$ is the time between two long data frame and represents the time that does not contribute to the duty cycle. $T_{Off\ Time}$ is the sum of T_{ACK} , T_{RX_ACK} , $T_{Process}$, and $T_{Ave\ Backoff}$ which calculates to 3.864 ms.

T_{Total} is the total cycle time from the beginning of one long data frame to the beginning of the subsequent data frame. T_{Total} is $T_{On\ Time} + T_{Off\ Time} = 8.12$ ms.

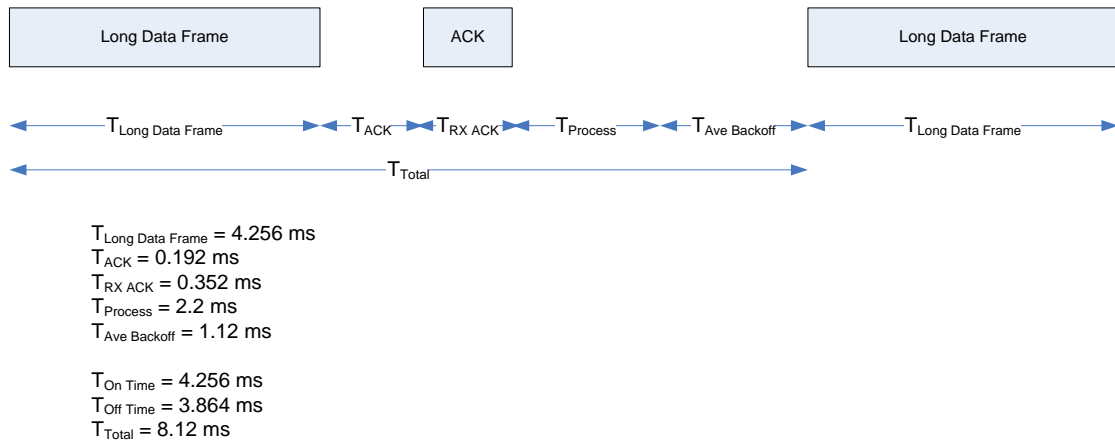


Figure 2. Sending Max Data Frame with ACK Received

Within a 100 ms period as many as 12 long data frames can be transmitted (100 / 8.12 = 12.3). In accordance with FCC, we calculate duty cycle as the percentage of time the radio is in TX mode per 100 ms period during maximum (continual) packet transmission.

The maximum duty cycle can therefore be calculated as:

$$\text{Duty Cycle} = T_{On\ Time} / T_{Total} = 4.256 / 8.12 = 52.41\%$$

$$\delta = 20 \log_{10} 0.5241 = -5.61\text{ dB}$$

5.1.2 Empirical Analysis

The Z-Stack TransmitApp is designed to transmit data as fast as possible, therefore maximizing duty cycle by maximizing utilization of the channel. Measure duty cycle by sending maximum length packets between two devices running Z-Stack TransmitApp without any other network participants or interference sources. For TransmitApp the data payload length is provided by the function `afDataReqMTU()` so that the total length of the frame including APS, NWK, and MAC overheads can be the maximum possible length.

The $T_{\text{Measured On Time}}$ is measured 4.424 ms. 12 TX/ACK pairs are measured in a 100 ms interval. The measured duty cycle can therefore be calculated as:

$$\text{Duty Cycle} = 12 \times T_{\text{Measured On Time}} / 100 = 53.08 \%$$

$$\delta = 20 \log_{10} 0.5308 = -5.50 \text{ dB}$$

5.2 Case 2: Maximum Length Frame with ACK Missed

Calculate the theoretical and empirical duty cycle for a maximum length frame sent with acknowledgement requested but no acknowledgement received. For the empirical analysis, this is accomplished by establishing a link between a sender and receiver running TransmitApp, and then turning off the receiver so no packet is received and no acknowledgement is sent.

5.2.1 Theoretical Analysis

$T_{\text{Long Data Frame}}$ is 4.256 ms as explained in 5.1.1.

$T_{\text{ACK Wait}}$ is the timeout period when an ACK is not received in response to the long data frame. This corresponds to the *macAckWaitDuration* as defined by the IEEE 802.15.4-2006 specification [2] section 7.4.2 MAC PIB attributes and is 54 symbol periods or 864 μs .

T_{Process} is the processing time from the point of failing to receive the ACK to the point of starting the process of transmitting another data frame. For CC253X, this processing time is 0.6ms.

$T_{\text{Ave Backoff}}$ is 1.12 ms as explained in 5.1.1.

$T_{\text{On Time}}$ is 4.256 ms as explained in 5.1.1. This is the on-air TX time that contributes directly to duty cycle.

$T_{\text{Off Time}}$ is the time between two long data frame and represents the time that does not contribute to the duty cycle. $T_{\text{Off Time}}$ is the sum of $T_{\text{ACK Wait}}$, T_{Process} , and $T_{\text{Ave Backoff}}$ calculates to 2.584 ms.

T_{Total} is the total cycle time from the beginning of one long data frame to the beginning of the subsequent data frame. T_{Total} is $T_{\text{On Time}} + T_{\text{Off Time}} = 6.84$ ms.

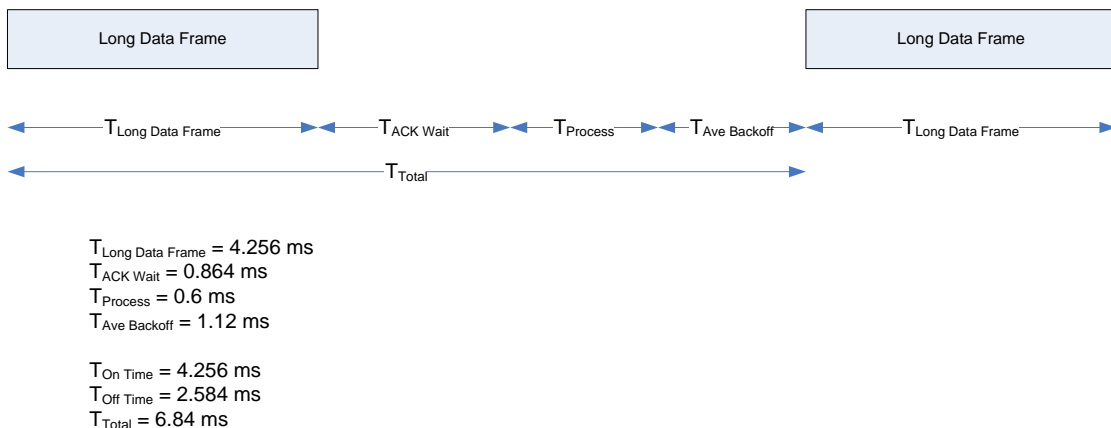


Figure 3. Sending Max Data Frame with ACK Missed

When an acknowledgement is not received by the sender, the long data frame is retried four times by the MAC layer before a send failure is reported to the application. After this it is left to the application to initiate a new transaction. When maximizing duty cycle, consider the case where the application, upon receiving the send failure, retries indefinitely as fast as possible. Because it takes time for the application to handle the failure and retry sending the packet, we must include an application processing time $T_{App\ Process}$ to our calculation.

$T_{App\ Process}$ is the application processing time, from the point of receiving the transmission failure to the point of retrying a new application data transmission. This value has been empirically calculated as 1.54 ms for Z-Stack TransmitApp, but should be empirically determined or controlled for the specific application.

T_{MAC} is the total time spent during a data transmission in the MAC layer. T_{MAC} is $T_{Total} * 4$ MAC retries = 27.36 ms.

$T_{App\ On\ Time}$ is the portion of the T_{MAC} time when the transceiver is in TX mode. $T_{App\ On\ Time}$ is calculated as $T_{On\ Time} * 4 = 17.024$ ms.

$T_{App\ Off\ Time}$ is remaining time when the transceiver is not in TX mode during T_{MAC} , plus the additional application processing time ($T_{App\ Process}$) where the transceiver is also not transmitting. $T_{App\ Off\ Time} = T_{Off\ Time} * 4 + T_{App\ Process} = 11.876$ ms.

$T_{App\ Total}$ is the total cycle time from the beginning of one long data frame to the beginning of the subsequent application data frame retry. $T_{App\ Total}$ is $T_{App\ On\ Time} + T_{App\ Off\ Time} = 28.9$ ms.

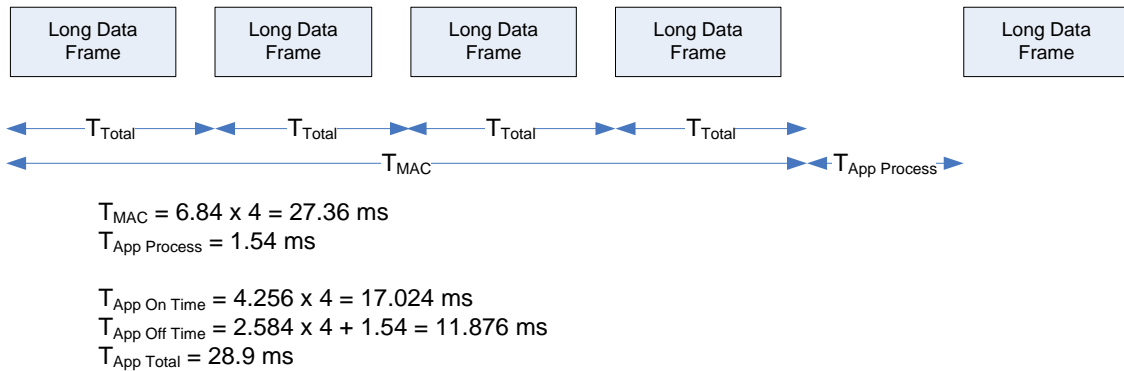


Figure 4. Sending and Retransmitting Max Data Frame with ACK Missed

Within 100 ms, as many as 3 application retries can be attempted ($100 / 28.9 = 3.46$). The maximum duty cycle can be calculated as:

$$\text{Duty Cycle} = T_{App\ On\ Time} / T_{App\ Total} = 17.024 / 28.9 = 58.91 \%$$

$$\delta = 20 \log_{10} 0.5891 = -5.00 \text{ dB}$$

5.2.2 Empirical Analysis

Here the Z-Stack TransmitApp is used for the reasons described in 5.1.2.

The $T_{Measured\ On\ Time}$ is measured as 4.224 ms and 14 TX frames are measured in a 100 ms interval. The measured duty cycle can therefore be calculated as:

$$\text{Duty Cycle} = 14 \times T_{Measured\ On\ Time} / 100 = 59.14 \%$$

$$\delta = 20 \log_{10} 0.5914 = -4.56 \text{ dB}$$

6 Using This Application Note

This application note serves to help Z-Stack users through a basic analysis for calculating duty cycle both theoretically and empirically for the maximum throughput application, TransmitApp. We run our example with only two nodes, a sender and receiver, and no additional communication interference, routed packets, or data throughput in the system. One can expect that any additional communication, routing, administrative packets or additional interference in the system would only serve to delay communication, limit on-air (TX) time, and therefore lower duty cycle. By performing the analysis within the constraints of a simple network one can determine the worst case duty cycle created by the application to ensure that under “perfect” conditions a device will be within the FCC, ETSI, or ARIB requirements as stated. A designer seeking to limit the TX duty cycle of a ZigBee node can manipulate T_{App} _{Process} or MAC parameters to achieve the desired δ . This will of course impact on the throughput of the node.

References

- [1] FCC Title 47 CFR Part 15 Specification
- [2] IEEE Std 802.15.4-2006 Specification
- [3] ZigBee Specification
- [4] CC253X User's Guide ([swru191b.pdf](#))
- [5] Using CC2591 Front End with CC2530 and CC2531 ([swra308a.pdf](#))
- [6] Z-Stack Developer's Guide ([xxxx.pdf](#))
- [7] Z-Stack Sample Applications (swra201.pdf)

7 General Information

7.1 Document History

Revision	Date	Description/Changes
SWRA396	January 2012	Initial release.

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