Z-Stack
User's Guide For
CC2530 ZigBee-PRO Network Processor
Sample Applications

ZigBee-2007 Release
Version 2.3.1-1.4.0

Document Number: SWRU242

Texas Instruments, Inc.
San Diego, California USA

Revision	Description	Date
1.0	Initial release	01/18/2010
1.1	Small corrections (Link Status messages, etc.)	01/21/2010
1.2	Updated for Z-stack 2.3.1 release. Document modifications include support for installing Certicom keys in the CC2530 lock bits flash. Enhanced Chapter 3 for ZNP SBL and Chapter 4 for ZAP Proxy to SBL	08/02/2010

Table of Contents

Table of Figures

Abbreviations

AF	Application Framework
API	Application Programming Interface
BB	Battery Board
CBKE	Certificate-based Key Establishment
DUT	Device Under Test
EB	Evaluation Board
ECC	Elliptic Curve Cryptography
EM	Evaluation Module
ESP	Electronic Service Portal
HA	Home Automation
HAL	Hardware Abstraction Layer
HAN	Home Area Network
HW	Hardware
IPD	In-Premise Display
OSAL	Operating System Abstraction Layer
OTA	Over-the-Air – refers to the process of and/or the ZCL for transmitting and installing a new image in a device remotely via over-the-air messages.
PCT	Programmable Communicating Thermostat
SBL	Serial Boot Load – the capability to install a new image via a serial connection such that the new image is installed directly and the receiving device does not need extra non-volatile storage space to first store the new image before actually installing it (e.g. a necessary intermediate step in OTA.)
SBL	Serial Boot Loader – refers to the embedded code that implements SBL capability.
SE	Smart Energy
SNA	Sensor Network Analyzer
SoC	System on a Chip
SW	Software
TVSA	Temperature Voltage Sample Application
ZAP	ZigBee-PRO Application Processor
ZCL	ZigBee Cluster Library
ZDO	ZigBee Device Object
ZNP	ZigBee-PRO Network Processor

1. Introduction

This document accompanies the Texas Instruments Z-Stack™ solution for use with the CC2530 ZigBee® Development Kit. The Z-Stack software (www.ti.com/z-stack) is a complete protocol stack and application development solution that conforms to ZigBee Alliance standards (www.zigbee.org).

The purpose of this document is to explain the setup and usage of the sample applications that are provided to create an MSP430-based ZigBee Application Processor (ZAP) that utilizes a CC2530/CC2531 SoC-based ZigBee-PRO Network Processor (ZNP) to communicate over a ZigBee network. Before addressing the different sample applications (Chapter 4) it is shown which hardware setup to use (Chapter 3) and how to build the ZNP image (hex-file) that needs to be programmed onto a CC2530/CC2531 (in the following simply referred to as SoC) to turn it into a ZNP (Chapter 3). In the FAQ section towards the end of document, FAQs are addressed while the References to other documentation can be found in Chapter 5.

Figure 1 illustrates how easy an application processor can be connected to the SoC based ZNP to obtain ZigBee connectivity. The ZAP describes the Processor/MCU that is running the application code, which is using the CC2530-ZNP API over the UART/SPI/USB interface to communicate with the ZNP, which is running the full Z-Stack and hence provides the ZigBee connectivity with its IEEE 802.15.4 radio.

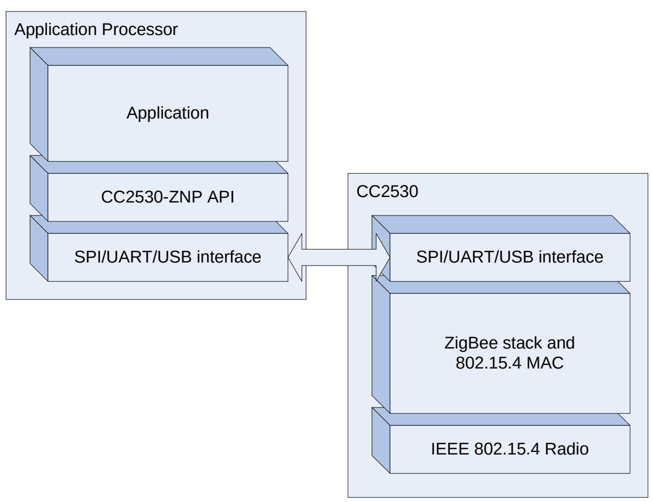


Figure 1: Interaction between the ZAP and the ZNP

For more technical details regarding the usage of the Z-Stack in general (partially also applicable for the ZNP) the reader is referred to the Z-Stack documentation, where one should start with the *Z-Stack Developer's Guide* [1]. The details of the ZNP interface are described in the *CC2530-ZNP Interface Specification* [2].

Although the sample application examples utilize an MSP430 CPU, the ZAP could be any MCU that supports the SPI/UART/USB connectivity to the ZNP (e.g. a Stellaris Cortex-M3 or a

Windows PC application). Only the HAL and OSAL specific components would need to be ported to the other platform.

For general documentation regarding the Z-Stack the reader is first referred to the Z-Stack Developer's Guide and the Z-Stack User's Guide of the respective platform, which can be found in the platform specific folder in the Z-Stack documentation folder (*C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents)*; for example for the CC2530 it is placed in: *C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents\CC2530* (if you use the default installation directory). After reading those Z-Stack guides the reader can find more detailed information in the other Z-Stack documents.

2. Assumptions

1. All paths shown in text and figures assume that the Z-Stack was installed in the default directory of the "C:" drive.

3. CC2530 ZNP Software and Hardware Description

After a short description of the development system requirements (Section 2.1), this Chapter describes the software (Section 2.2) and hardware (Section 2.3) required for running and working with the sample applications for the CC2530-ZNP.

2.1. Development System Requirements

The ZAP sample applications and the ZNP Z-Stack projects are based on the IAR ***Embedded Workbench*** (EW8051 [3] and MSP430 [4]) suite of software development tools. These tools support project management, compiling, assembling, linking, downloading, and debugging.

The Texas Instruments ***SmartRF Flash Programmer*** [5] is a tool that provides various programming capabilities when using SmartRF based development kits.

Chapter 3 explains how to use the IAR Embedded Workbench and the SmartRF Flash Programmer to build a ZNP image (hex-file) and then program it onto the SoC. The usage of the sample application projects for the ZAP is addressed in Chapter 4.

In order to modify, build, and use the ZNP image and the ZAP sample applications (and to program the resulting images onto the hardware the following software and development tools are required:

- For the ZNP: IAR Systems *Embedded Workbench for 8051* [3]
- For the ZAP (MSP430 based): IAR Systems *Embedded Workbench for MSP430* [4]
- For programming the hardware: Texas Instruments *SmartRF Flash Programmer* [5]
- ZNP-Software: Texas Instruments Z-Stack – version *ZStack-CC2530-2.3.1-1.4.0* or newer [6]
- ZAP-Software: ZAP sample application installer ZAP-MSP430-1.0.0 or newer [7]

For details regarding their installation the reader is referred to the corresponding documentation for each of the installers and tools.

2.2. CC2530 ZNP Software

All you need to build your own CC2530/CC2531 based ZNP is a ZNP image (hex-file), which you can program onto the SoC using the SmartRF Flash Programmer [5].

The software required to build a ZNP image (hex-file) is part of the "full" Z-Stack installation package [6] (version *ZStack-CC2530-2.3.1-1.4.0* or newer) that contains all of the documentation and software required to install, configure, and develop applications using Z-Stack. Documentation regarding the Z-Stack can be found in the Z-Stack documentation folder:
C:\Texas Instruments\ZStack-<platform>-<stack-version>-<applications version>\Documents
e.g. C:\Texas Instruments\ZStack-CC2530-2.3.1-1.4.0\Documents
(if you use the default installation directory).

The software required to build a ZNP image (hex-file) is provided in form of a Z-Stack project, named ZNP. Details on how to use this project to build the ZNP image is given in Chapter 3.

The software required to build a ZAP image (hex-file) for a MSP430 based application processor is provided in form of an additional installer [7]. The different projects and their usage are addressed in Chapter 4.

Note: The ZNP software is part of the "full" Z-Stack installer [6] targeting the CC2530 platform and it requires the IAR EW8051 [3] in case you want to build your own ZNP images (hex-files). The ZAP software provided for the MSP430 (see Chapter 4) comes in a separate sample application installer [7], which requires the IAR EW430 [4]. In case you have ready-built ZNP images you do not need to install the ZNP software and the IAR EW8051; instead the only additional tool you need to build a ZNP is the SmartRF Flash Programmer [5] to program the ZNP image onto the SoC.

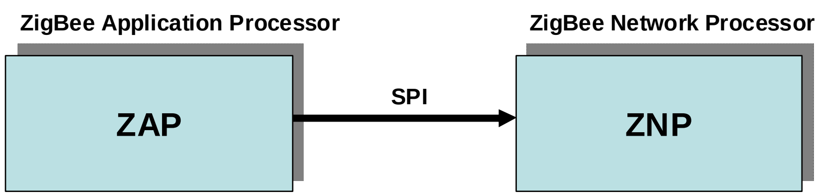
2.3. CC2530 ZNP Hardware

The ZNP can be built using Texas Instruments ZigBee-PRO capable system on chip (SoC) devices; i.e. either CC2530 [8] or CC2531 [9]. The details on how to connect the SoC to the ZAP via SPI/UART/USB are described in detail in the *CC2530-ZNP Interface Specification* [1]. The following subsections address different hardware setups for a ZNP based development. The first sections (2.3.1-2.3.4) describe several possible setups, as one already might own different development boards; however, if you do not have any development boards yet, you should jump straight to Section 2.3.5

For more detailed information regarding the different development boards the reader is referred to the corresponding user guides.

2.3.1. MSP430 based hardware setup used for the sample applications

The sample applications in Chapter 4 are based on the CC2530 as ZNP and a MSP430 (MSP430F2618 / MSP430F5438) as ZAP (see Figure 2).



Option-1: MSP-EXP430F5438

Option-2: CCMSP-EM430F2618 & SmartRF05EB

Option-1/Option-2: CC2530EM

Figure 2: HW combinations used for Sample Applications

The CC2530 development board used for the sample applications is the CC2530EM (CC2530 Evaluation Module) shown in Figure 3. The CC2530EM is the reference design for the usage of CC2530 and it is used in all CC2530 development kits (CC2530DK and CC2530ZDK). For more details about the different CC2530 development boards/tools/kits the reader is referred to the *Tools & Software* section of the CC2530 product folder [8].

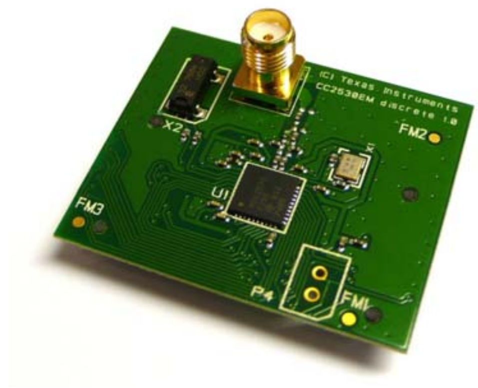


Figure 3: CC2530 Evaluation Module (CC2530EM)

The development boards used for the ZAP are the CCMSP-EM430F2618 & SmartRF05EB for the MSP430F2618 (see Figure 4) and the MSP-EXP430F5438 for the MSP430F5438 (see Figure 5). Both board setups have the connectors required to plug in a CC2530EM.

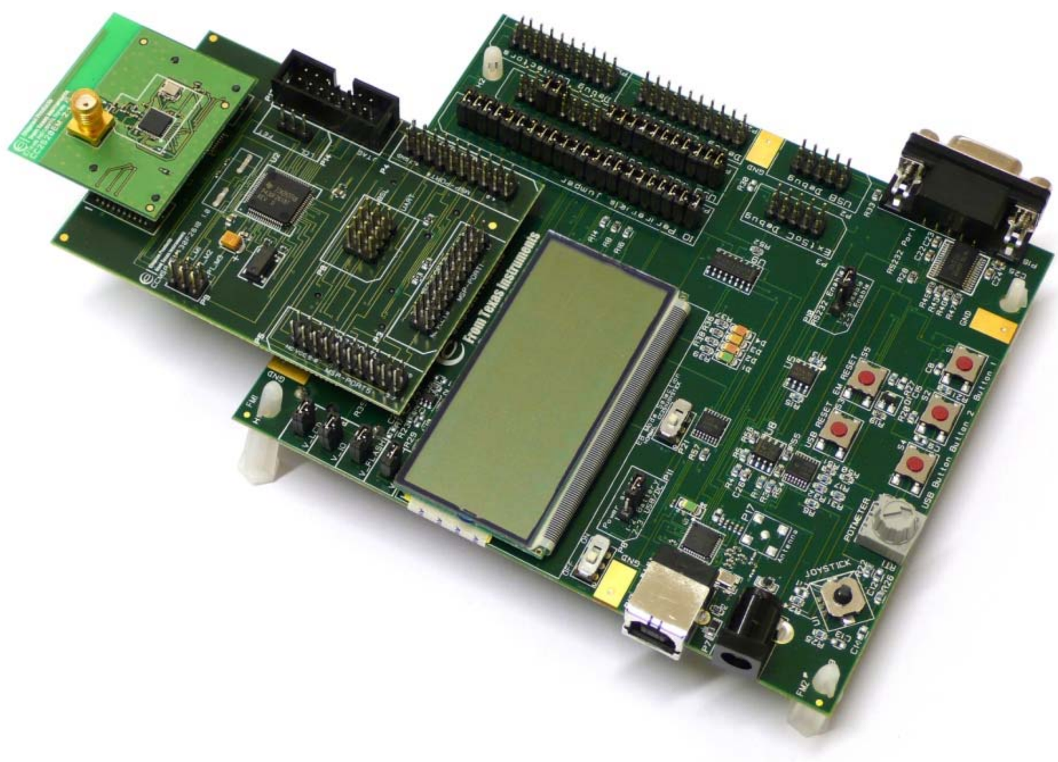


Figure 4: CCMSP-EM430F2618 & SmartRF05EB with an EM plugged in

Figure 5: MSP-EXP430F5438 with EM and MSP-FET430UIF

2.3.2. Hardware setup for a USB connected ZNP

The CC2531USBDongle (see Figure 7) is a third HW option to work with a ZNP; however it does not provide an MCU that could act as ZAP. The dongle is based on a CC2531 [9]; i.e. providing an on-chip USB interface to the ZNP that one could use via a PC application (that acts as ZAP); see Figure 6. However, as it is not used in the sample applications (described in Chapter 4) it is not further addressed in this document.

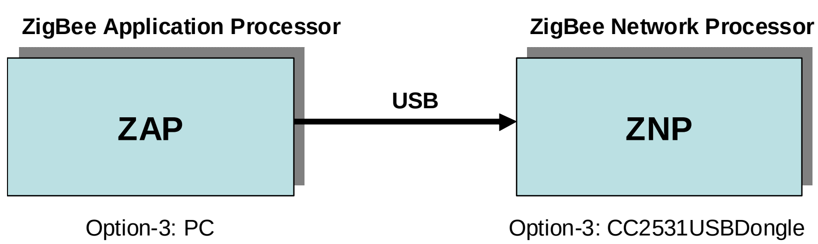


Figure 6: Principle for using the CC2531USB Dongle as ZNP

Figure 7: CC2531USBDongle

2.3.3. Hardware for programming the CC2530EM

To program the ZNP image (hex-file) with the SmartRF Flash Programmer onto a CC2530EM, the EM needs to be plugged directly into one of the following boards: SmartRF04EB, SmartRF05EB (see Figure 8), SmartRF05BB, or SoC_BB board. The latter two boards, also known as battery boards, also require the CC-Debugger [10] (see Figure 9) for programming.

Figure 8: CC2530EM plugged into a SmartRF05EB for programming

Figure 9: CC-Debugger

2.3.4. Hardware for programming the CC2531USBDongle

The CC2531USBDongle can be programmed by using the little 10 pin connector marked *Debug*. Simply use the adapter cable (shipped with the CC2530DK, CC2530ZDK or the CC-Debugger) to connect the *Debug* connector with the ExtSoC Debug connector on a SmartRF05EB (see Figure 10) or the CC-Debugger. Then use the SmartRF Flash Programmer that should be able to recognize the CC2531 SoC to program the CC2531. More info can be found on the CC2531EMK product folder [11].

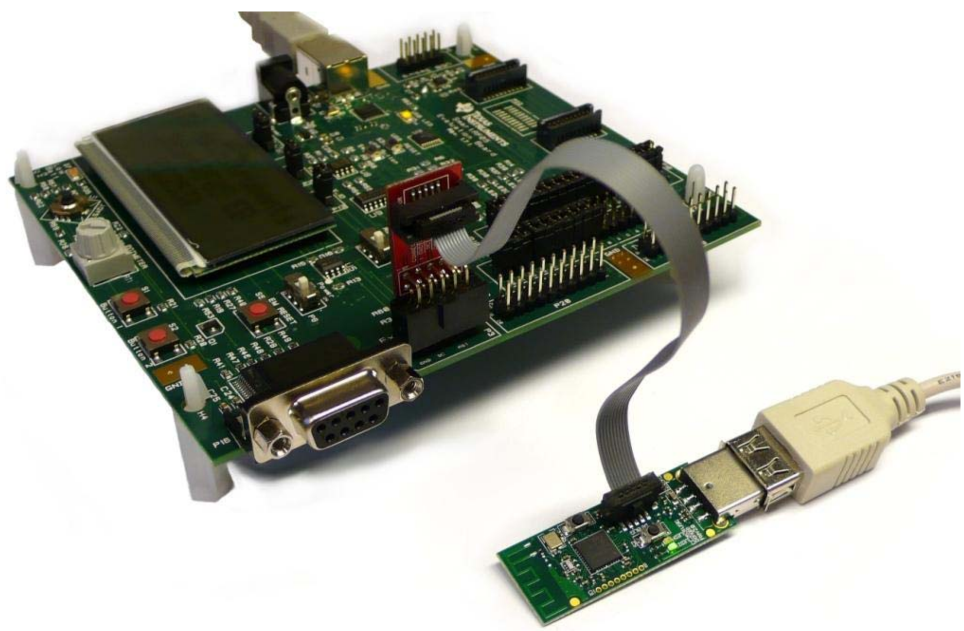


Figure 10: Programming the CC2531USBDongle using the SmartRF05EB

2.3.5. Easiest and quickest hardware choice

The reader, unfamiliar with the CC development HW and tools, easily gets confused about which HW combination to choose, when reading the above sections (2.3.1-2.3.4). While the sections above are useful to those that already have HW from other development activities it is recommended for the new-comer to simply order a CC2520DK and a CC2530EMK (Figure 11). The CC2520DK will provide you with twice the HW shown in Figure 4 (2 x CCMSP-EM430F2618, 2 x SmartRF05EB, and 2 x CC2520EMs) and the CC2530EMK will provide you the correct EMs to be used as ZNPs (as shown in Option-2 in Figure 2).

Figure 11: CC2530EMK

3. Building the ZNP needed for the sample application

This chapter explains how to build a ZNP image (hex-file) and how to program it onto the SoC that is targeted to act as a ZNP. It also gives additional information at the end on how to change some of the ZNP settings.

3.1. ZNP Software project files

As stated in Section 2.2, the Z-Stack project that builds a ZNP image is named ZNP, as shown in Figure 12, and the corresponding project workspace file, *znp.eww*, can be found in the folder shown in Figure 13.

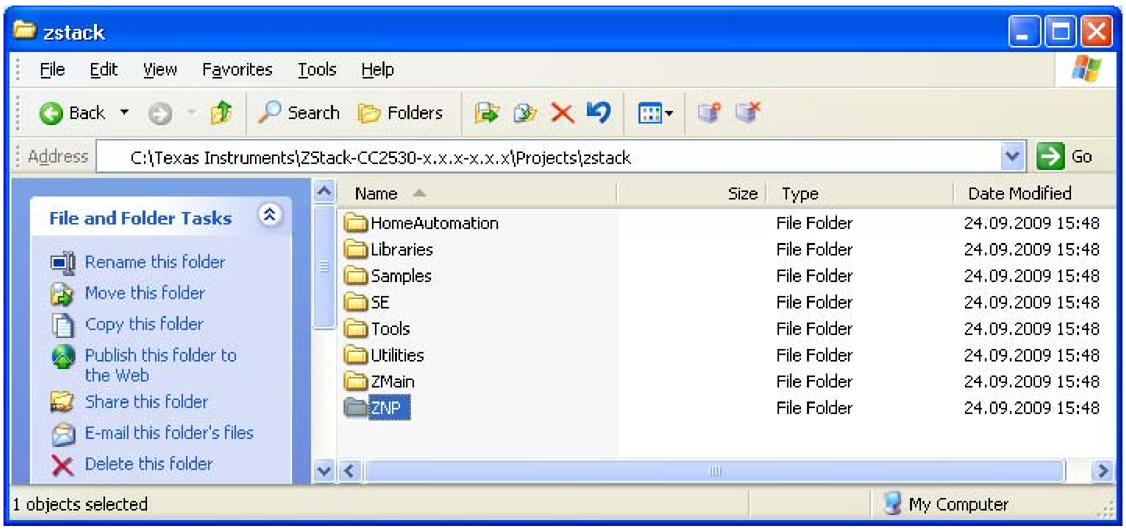


Figure 12: Location of the ZNP project.

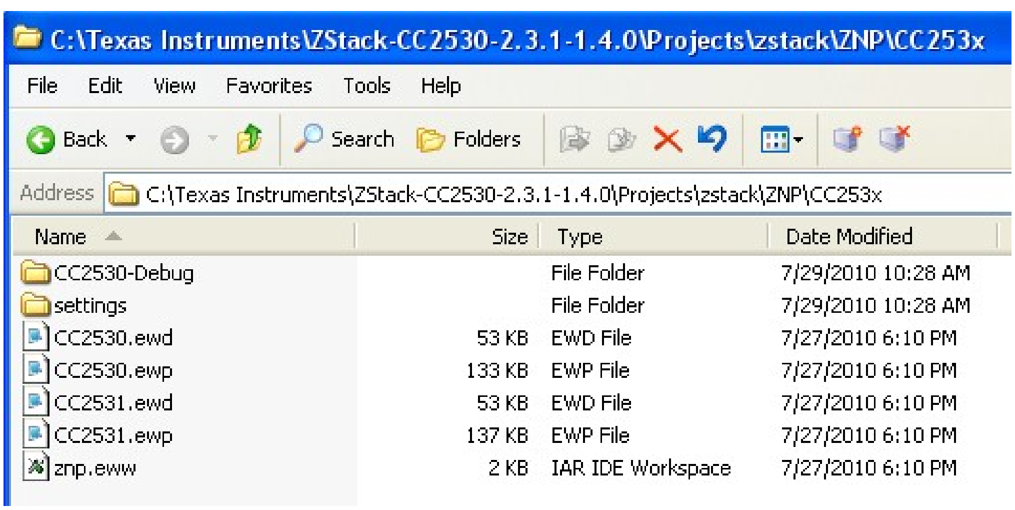


Figure 13: Location of the ZNP workspace file.

In order to get started simply open the workspace file *znp.eww* in the IAR Embedded Workbench for the SoC (EW 8051 [3]); see Figure 14. Sections 3.2, 3.3, and 3.4 illustrate how to compile and program the various ZNP images. Section 3.5 shows how to change the settings if required.

Note: Please check the *ZStack-CC2530 Release Notes* in the *README CC2530 Full.txt* file to see which version of the IAR EW 8051 is required. The file can e.g. be found in the platform specific directory: *C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents\CC2530.*

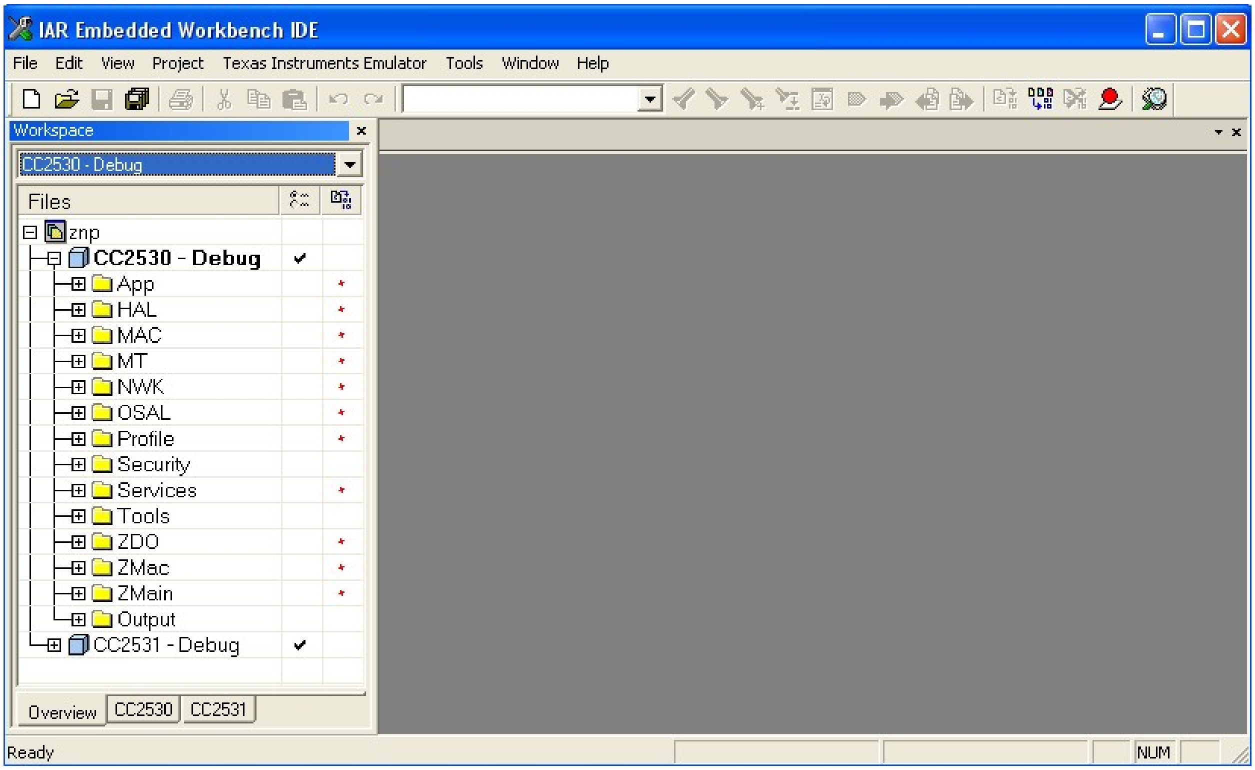


Figure 14: View after opening znp.eww in the IAR EW 8051

3.2. Compiling a ZNP image (hex-file)

In this section it is shown how to compile a ZNP image based on the current settings in the opened workspace For details on how to change the settings (e.g. channel, PAN ID) please see Section 3.5. For more detailed information regarding the usage of the IAR Embedded Workbench the reader is referred to the IAR documentation; e.g. starting with the EW8051 User Guide [13].

As a first step, one has to choose the correct workspace setup from the 8 available configurations. These configurations are provided so that users can automate the build of the ZNP image to suit their desired need.

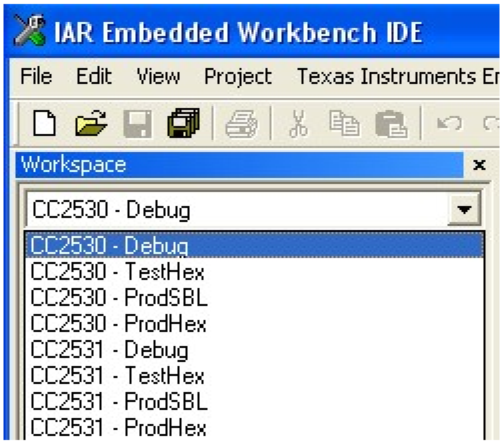


Figure 15: Workspace setup

CC2530 - Debug – this configuration produces a debuggable ZNP image that is downloaded and run from the IAR IDE with the out-of-box settings from f8wConfig.cfg and znp.cfg. The linker file associated with this configuration does *not* reserve a CODE segment for the serial boot loader.

CC2530 - TestHex – this configuration produces an intel-extended-hex image that would be loaded using a flash programming tool such as the TI SmartRF flash programmer. The linker file associated with this configuration does *not* reserve a CODE segment for the serial boot loader.

This project has the following compile options (which override the out-of-box settings in f8wConfig.cfg and znp.cfg). These extra options facilitate ZigBee Smart Energy testing.

```
ASSERT_RESET
MT_SYS_OSAL_NV_READ_CERTIFICATE_DATA=TRUE
MT_SYS_KEY_MANAGEMENT
ZCL_KEY_ESTABLISH
TC_LINKKEY_JOIN
SECURE=1
```

The `MT_SYS_OSAL_NV_READ_CERTIFICATE_DATA=TRUE` and `MT_SYS_KEY_MANAGEMENT` compile option settings are used to allow the user to be able to initialize and retrieve the security keys and certificate data by using MT (e.g. via Z-Tool or ZAP applications). While this is ok for test and debug purposes, users should strongly consider turning off these compile option settings for production devices to prevent any access to established link keys or Certicom certificate data.

CC2530 - ProdSBL – This configuration produces an image to be loaded via the serial boot loader using a PC tool, such as SBDemo.exe, which is discussed in Section 4.5.3. The out of box configuration settings from f8wConfig.cfg and znp.cfg are used.

CC2530 - ProdHex – This configuration produces an image that would be loaded using the SmartRF flash programmer. The linker file associated with this configuration *does* reserve a CODE segment for the serial boot loader and thus the resulting output of this build includes the ZNP firmware plus serial boot loader. The out of box configuration settings from f8wConfig.cfg and znp.cfg are used. Because this image includes the serial boot loader, the .bin file from the build output of CC2530 - ProdSBL can be downloaded using the SBDemo.exe as well.

CC2531 configurations are analogous versions of the above.

In the remainder of this section the setup “CC2530 - TestHex” is chosen as that is the one used primarily for testing the ZNP.

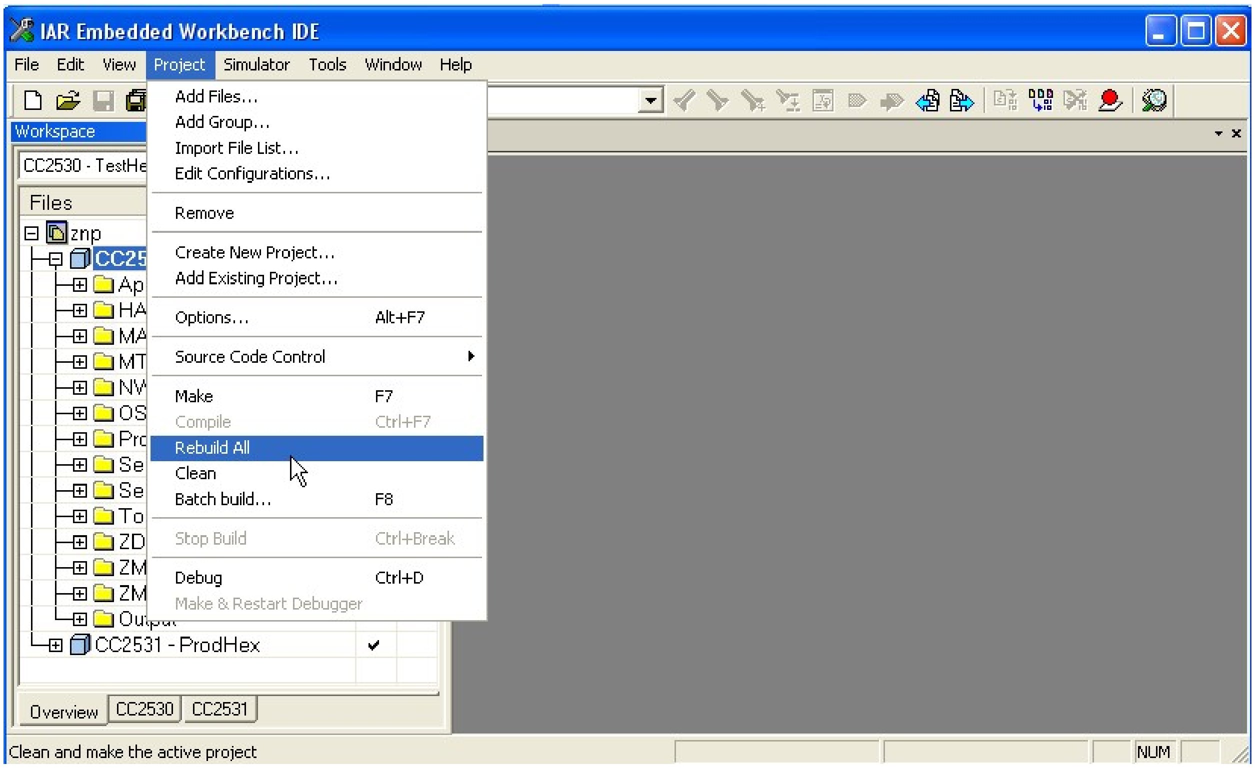


Figure 16: Starting the compilation and build of the ZNP image

After the build has been finished successfully (i.e. there are neither warnings nor errors) as shown in Figure 17, the resulting hex file can be found in the following directory:
C:\TexasInstruments\ZStack-CC2530-x.x.x-x.x.x\Projects\zstack\ZNP\CC253x\dev.
The next section shows how this resulting hex-file now can be programmed onto the SoC.

Note: When looking at the file size do not get confused by the info displayed/offered by Windows as that number is often far too high and if it would be the real file size the image would never fit into the flash of the SoC. In order to get the correct image size one can check the output files generated by the IAR EW8051, by simply clicking the Output tap (at the end of the project setup tree) and opening the *CC2530ZNP-Test.map* file. Useful information such as the image size is provided at the end (see also Figure 18).

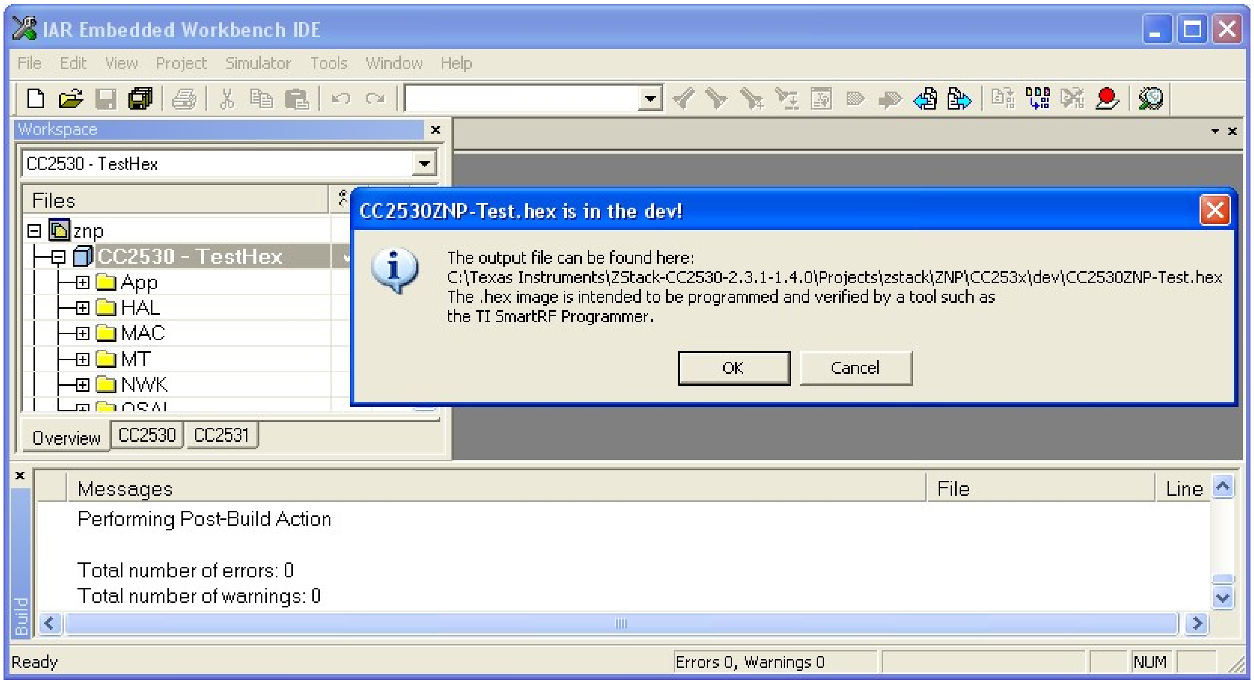


Figure 17: Successful build without any warnings or errors

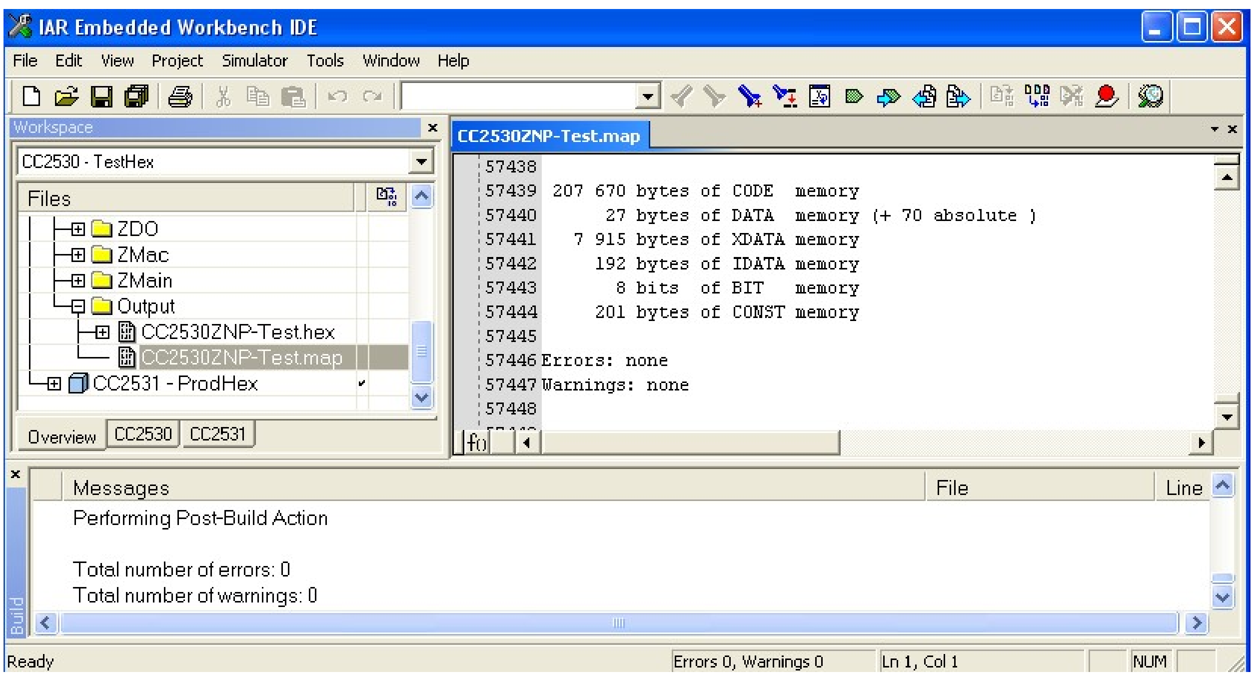


Figure 18: Map file with useful information (e.g. image size)

3.3. About the image with serial boot loader support

As previously mentioned, the CC2530 – ProdHex configuration builds a ZNP image with serial boot loader support.

The serial boot loader receives control from the reset vector and verifies whether valid ZNP code is present. If so, then the serial boot loader gives the host processor a window of time in which to force boot mode or an immediate jump to the ZNP code. The following rules apply to the serial boot loader:

1. If the CRC is not 0x0000 or 0xFFFF and the CRC-shadow is identical, then the ZNP code is valid.

2. If the CRC is not 0x0000 or 0xFFFF and the CRC-shadow is 0xFFFF, then the CRC is calculated over the ZNP code image area (this will take over a minute.)

   a. If the calculated CRC matches the read CRC, the CRC-shadow is programmed to this identical value to speed-up future power-ups.

3. If the ZNP code is valid, wait for the host processor to send a 0xF8 to force boot-mode or an 0x07 to force an immediate jump to the ZNP code.

   a. The default wait for UART and USB transport is 1 minute.
   b. The default wait for SPI is 50 milliseconds.

4. If the ZNP code is valid and the wait expires, jump to the ZNP code.
5. If the ZNP code is not valid, immediately jump to the boot-code without waiting as described above.

3.4. Programming the ZNP image onto the target

In this section it is shown how to load a ZNP image (hex-file) onto a SoC using the Texas Instruments SmartRF Flash Programmer [5].

To get started, simply open the SmartRF Flash Programmer and connect the device to be programmed to the PC (for the hardware-setup the reader is referred to Section 2.3) and turn the device on. If everything is setup correctly the device should show up as shown in Figure 19, indicating the EB ID, Chip type, EB type, EB firmware ID, and EB firmware ID rev.

As soon as the device to be programmed has been identified, the next step is to identify the image (hex-file) that is to be programmed onto the device. By pressing the browse button to the right of the *Flash image* field one can easily navigate to the location of the image. For the example given in Section 3.2 the location would be *C:\TexasInstruments\ZStack-CC2530-x.x.x-x.x.x\Projects\zstack\ZNP\CC253x\dev\CC2530ZNP-Test.hex* as shown in Figure 19.

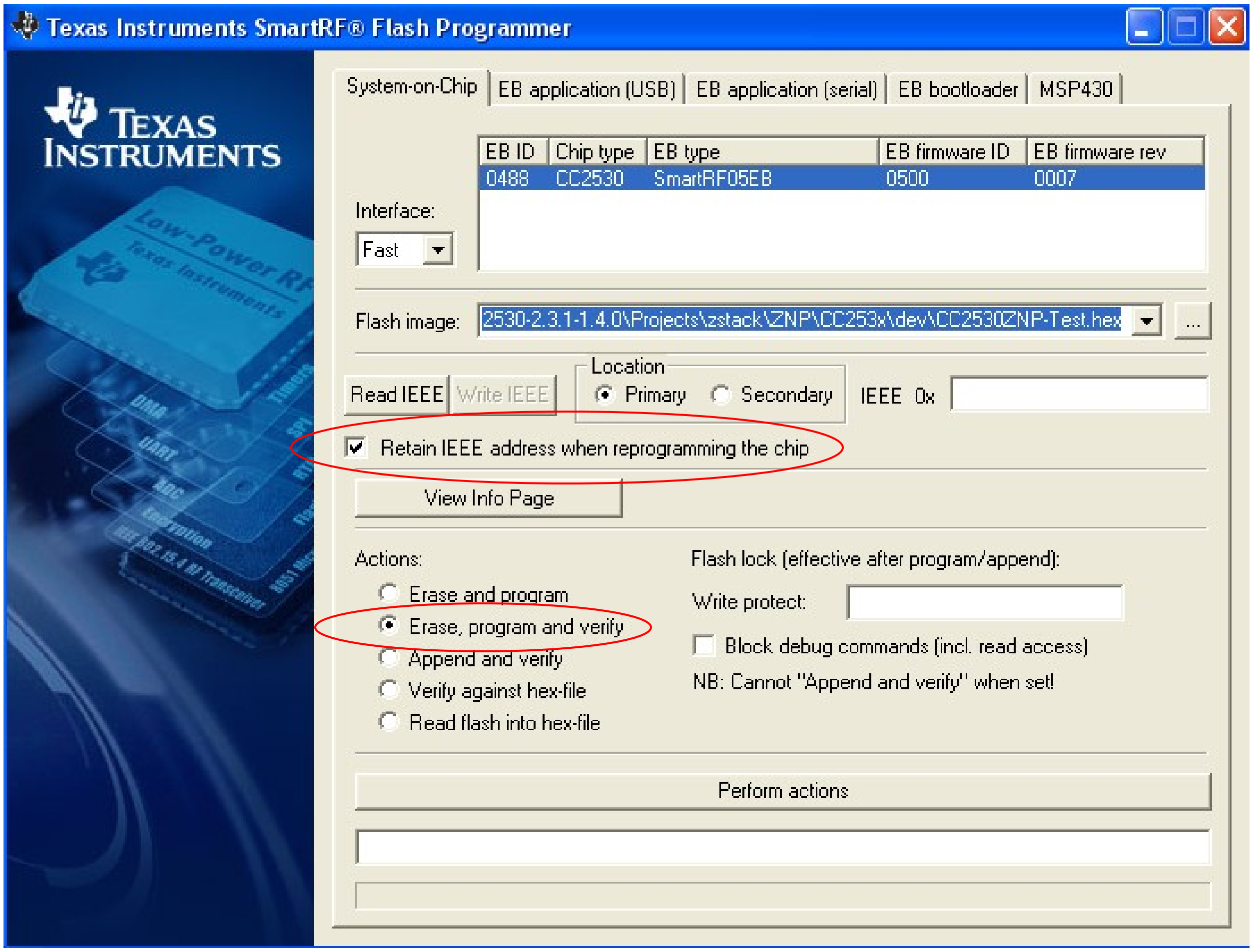


Figure 19: Screen shot from SmartRF Flash Programmer (before programming)

After checking that the *Retain IEEE address when reprogramming the chip* and the *Erase, program and verify* option are set (as shown in Figure 19) one only needs to press the *Perform actions* button in the bottom of the window.
As soon as the button has been pressed the status line in the bottom will display the progress/status. As soon as the programming has finished successfully the status line will display "*CC2530 – ID<EB ID>: Erase, program and verify OK*" as shown in Figure 20.

In case the above described procedure runs into issues please check the SmartRF Flash Programmer documentation [5] for resolution.

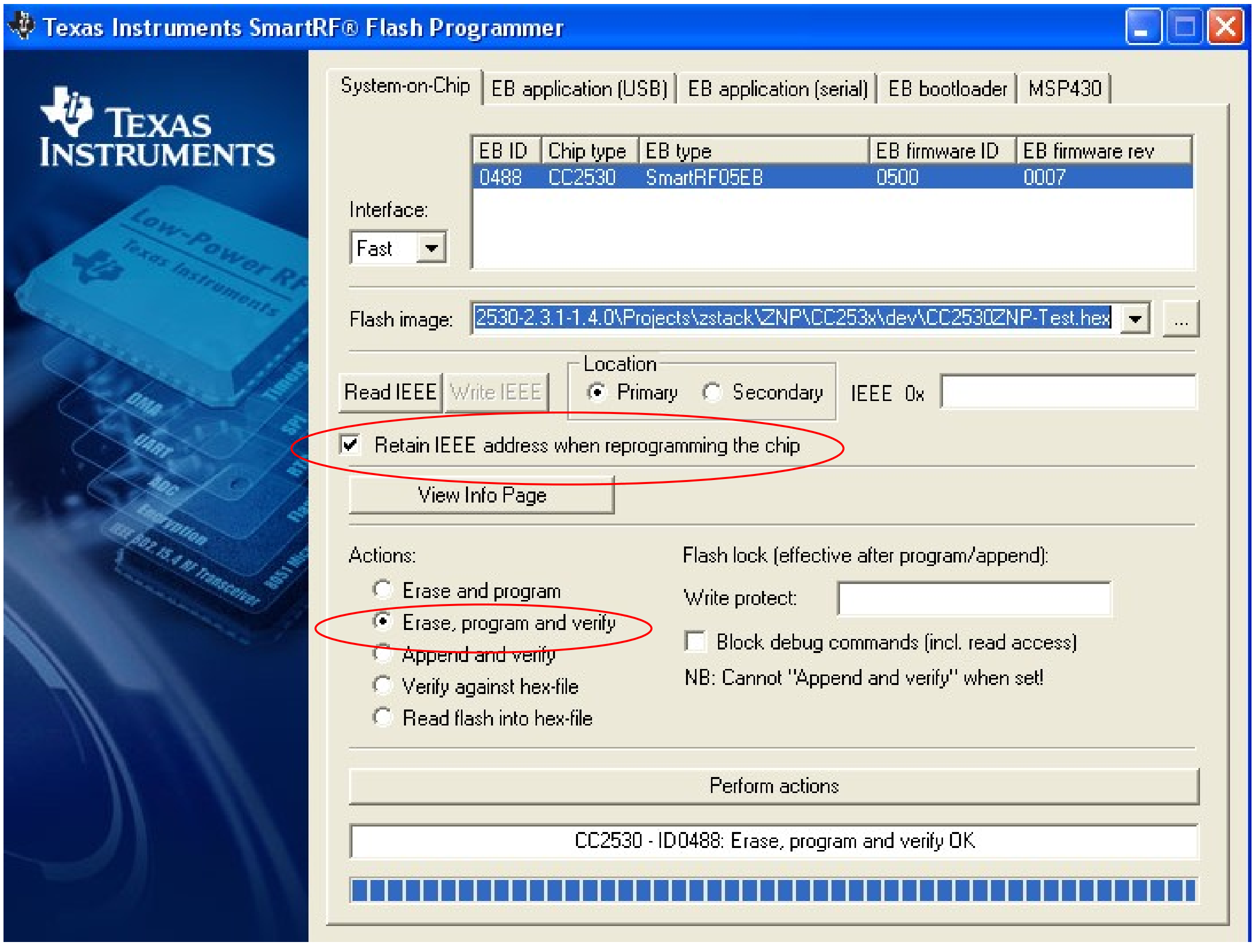


Figure 20: Screen shot from SmartRF Flash Programmer (after programming)

3.5. Changing settings in the ZNP project

While the previous sections in this chapter explained how to build a ZNP image and how to program it onto a SoC (to make it act as ZNP), this section briefly points to the configuration possibilities one has in order to build customized ZNP images. This is however only advised for experienced users of the Z-Stack that want to use a different image than the default out-of-the-box settings.

The recommended use of the ZNP is to use one of the pre-built hex-files that can be found in the *ZNP-HexFiles* folder as shown in Figure 21. For more details about those hex files please consult the readme file in that folder. When using the pre-built ZNP image (hex-file) one should only customize the configuration on the ZAP side (see Section 4.1.2).

To configure your customized ZNP image you would need to look at the *znp.cfg* and the *f8wConfig.cfg* for the ZNP project. Modifying the parameters in these two files is done in the same way as for a normal non-ZNP Z-Stack project; hence, one can find more information about the compile options and parameters in the standard Z-Stack documentation (after installing the Z-Stack [6] it can be found in C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents). A simple example is the enabling of the security feature. The ZNP image is built to support security by changing the -DSECURE=0 setting in *f8wConfig.cfg* to -DSECURE=1 (described in the Z-Stack Developer’s Guide [1], where it is also shown in the Security chapter how to adjust the NWK key and how to use a trust center link key).

4. Configuring and Using Z-Stack ZAP sample applications

After a general section describing the parts that are common for the different ZAP sample applications, additional sections describe the different ZAP sample applications in more detail.

ZAP sample applications [7]:

- **Temperature Voltage Sensor Application** (Section 4.2)
  This application establishes a sensor network where the sensor nodes report data to a central node, which is connected to a PC in order to display the data on the PC using a PC tool.

- **Home Automation Sample Application** (Section 4.3)
  This application provides the code to setup a switch device and a light device, where Home Automation Application Profile messages (using the ZigBee Cluster Library – ZCL), triggered by using the joystick, are used to toggle the LED on the light device

- **Smart Energy Sample Application** (Section 4.4)
  This application provides the code to setup different smart energy (SE) devices based on the Smart Energy Application Profile (using the ZigBee Cluster Library – ZCL) to

communicate with each other. Additionally it also illustrates how to setup the SE specific security (using special key establishment).

The sample applications are all using the *Operation System Abstraction Layer (OSAL)* and *Hardware Abstraction Layer (HAL)* concept known from the normal Z-Stack sample applications. For more details the reader is referred to the Z-Stack documentation (*C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents*) and especially the *HAL Porting Guide.pdf*.

The location of where to find the code for the different ZAP sample applications (after installing the corresponding software package *ZAP-MSP430-x.x.x.exe* [7]) is shown in Figure 21.

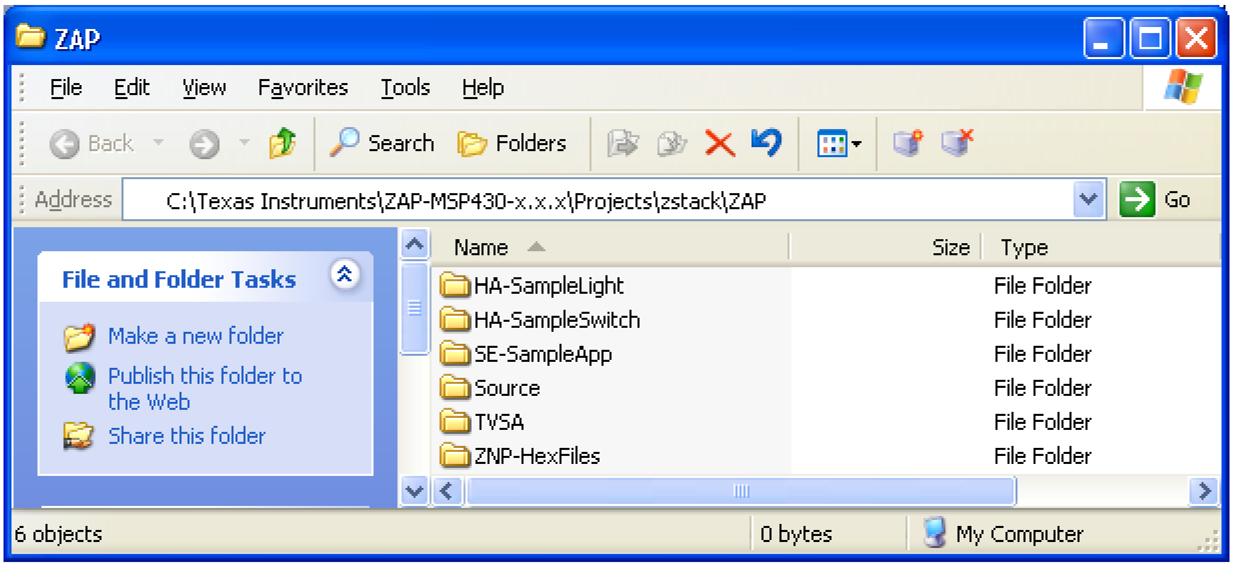


Figure 21: Location of the ZAP sample application code

4.1. ZAP Sample Applications Setup (general)

While the next sections provide specific information regarding the different sample applications for the ZAP, this sections addresses the general aspects that are the same for all of them.

4.1.1. Hardware

As described in Section 2.3 (Figure 2) there are two MSP hardware configurations that are supported by the ZAP sample applications: the CCMSP-EM430F2618 & SmartRF05EB for the MSP430F2618 (see Figure 4) and the MSP-EXP430F5438 for the MSP430F5438 (see Figure 5). Both board setups have the connectors required to plug in the CC2530EM (programmed to be a ZNP as explained in Chapter 3).

In order to program the MSP430 in each of the two setups one needs to use the MSP430 USB-Debug-Interface (MSP-FET430UIF) [15] that is provided together with the MSP430 development boards. The reader is referred to the CC2520DK User's Guide [16] for the details on its usage.

User interface

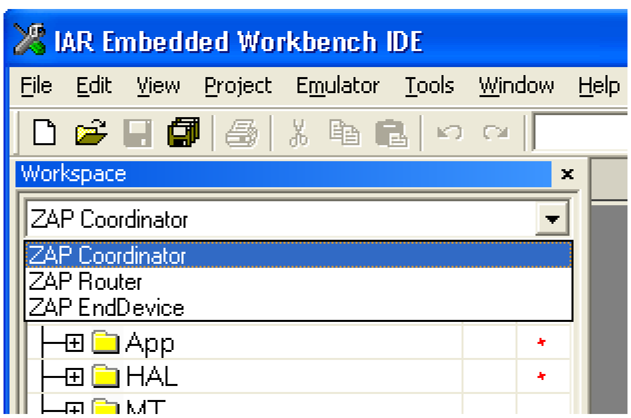
Each ZAP sample application requires a certain user interaction, which is enabled by an LCD display, LEDs, buttons and a joystick on the development boards. On the SmartRF05EB board the joystick is marked with *U1 – Joystick* on the PCB, while on the MSP-EXP430F5438 it is marked as *SW2* and a circle around it. Both are in the lower left corner of the boards. Please refer to the user guide's of the different hardware for further details [17] & [18].

4.1.2. Software

While the sample applications all have their own specific parameters they have certain things in common like ZigBee Device Selection, channel, PAN ID, etc.

ZigBee Device Type Selection

After opening the workspace file for the ZAP sample application the user can define the device type of the targeted node using one of the three options in the drop-down menu at the top left of the screen (see Figure 22).



ZAP Coordinator – This will set the project to program the device as ZigBee Coordinator.

ZAP Router – This will set the project to program the device as ZigBee router.

ZAP End Device – This will set the project to program the device as ZigBee End Device

Figure 22: ZigBee Device Type Selection (for TVSA and HA sample application)

ZAP configuration file

Each ZAP sample application workspace contains the ZAP configuration file *ZAP.cfg* (see Figure 23). This file contains a lot of the options required to setup the behavior of the resulting ZigBee node; e.g. which PAN ID to use or look for (using -*DZDAPP_CONFIG_PAN_ID*) or the channels to use (using -*DDEFAULT_CHANLIST*). For the details of how to set these parameters the reader is referred to the *Z-Stack Developer's Guide* [1] (Note: the naming of the parameters might be different; e.g. for the normal Z-Stack projects the PAN ID parameter is denoted by *ZDO_CONFIG_PAN_ID*).

The ZigBee 2007 specification defines the use of a 16-bit Personal Area Network Identifier (PAN ID) to uniquely identify a network. The ZAP sample application provides the user with two methods of selecting a PAN ID when starting or joining a network by setting the value of *DZDAPP_CONFIG_PAN_ID* in the *zap.cfg*. For a Coordinator device, setting this value to 0xFFFF, forces it to start a network with a PAN ID equal to the least significant 16-bits of its IEEE address. For a Router device, setting this parameter to 0xFFFF causes the device to join the "best" network it can discover within the specified channel list, any other value causes it to use the exact value specified. The "best" network is defined as the beacon response to scan commands that has the highest received signal strength (RSSI).

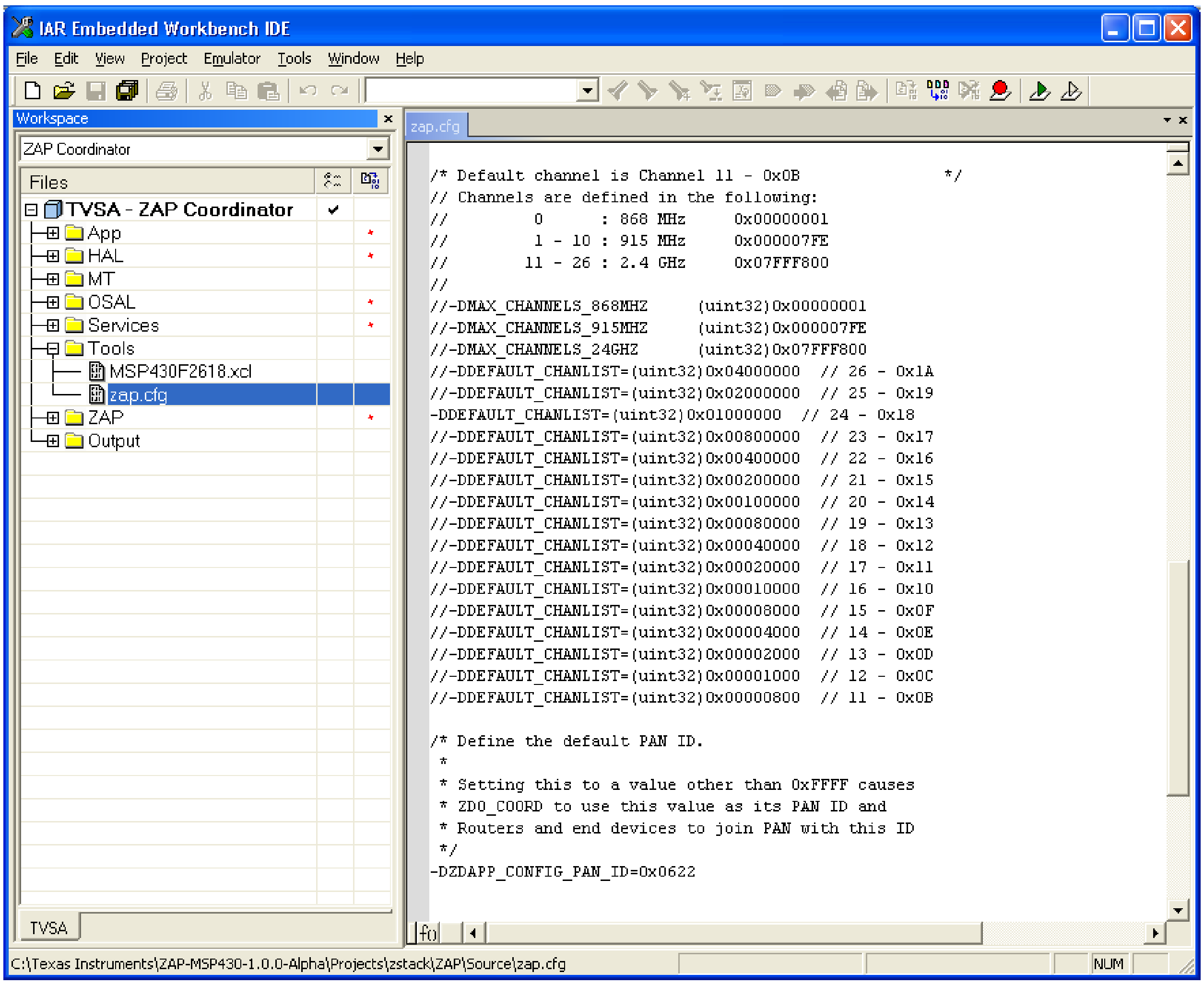


Figure 23: ZAP configuration file example configuring channel 24 – 0x18

The IEEE 802.15.4 specification defines 16 channels in the 2.4 GHz frequency range. These channels are assigned numbers 11 through 26. The Z-Stack initially defaults to channel 11, but the user can select a different channel by changing the -*DDEFAULT_CHANLIST* option in *zap.cfg*. This parameter is a bit map field, with each bit representing a single channel. The initial default channel 11 (0xB) is represented by 0x00000800 (11th bit in the field, starting from bit 0).

In order to save information that needs to be reserved during power off or reset of the device the Z-Stack uses NV (non-volatile) pages in the flash. The following parameters can be used to configure the NV usage:

The *ZAP_NV_RESTORE* compile option in *zap.cfg* determines whether or not the network state of the ZNP is restored after reset/power up. If *ZAP_NV_RESTORE* is set to FALSE the network state of the ZNP will be cleared and default configuration used for start up.

At startup, the ZAP makes a series of calls using *znp_nv_write* for the items *ZCD_NV_LOGICAL_TYPE*, *ZDAPP_CONFIG_PAN_ID*, *DEFAULT_CHANLIST* to configure the logical device type (coordinator, router, or end-device), PAN ID, and scan channel mask, respectively. The default values from the *zap.cfg* configuration file are taken as values. Note that this configuration of ZNP has been automated if the *ZAP_AUTO_CFG* compile option is set to TRUE in *zap.cfg*. This overrides the configuration values in *znp.cfg*.

The *ZAP_AUTO_START* compile option controls whether the device automatically starts up as a ZigBee device. If *ZAP_AUTO_START* is set to FALSE, the user application will have to manually call the *ZDOInitDevice* function to start the ZigBee functionality.

4.2. Temperature Voltage Sensor Application (TVSA)

The TVSA sample application is intended to show some basics of using the ZNP. In the TVSA network, several ZigBee nodes (ZigBee Routers or ZigBee End Devices) send temperature and voltage measurements at regular intervals to a central device (ZigBee Coordinator), which is called the “Dongle”. The Dongle collects this information and sends it to the PC, over a UART connection, for display. The Dongle acts as the ZigBee coordinator and the data collector point; hence, it does not report its own temperature and voltage. It interfaces over the UART connection to a PC tool called Z-Sensor Monitor Program (ZigBee Sensor Monitor) [14], which is available from the Texas Instruments Website (e.g. at www.ti.com/cc2530zdk). If desired the UART code on the dongle can easily be adjusted to fit the UART formatting used by other PC tools. The following sections provide more details regarding the usage and modification of the TVSA sample application.

4.2.1. Hardware and Software setup

To run this sample application you will need to build one ZAP Coordinator using the TVSA workspace file *TVSA.eww* (see Figure 21 for its location). Using the ZAP Coordinator workspace (see also Figure 22) will help you to set up the project for programming the device as a coordinator (i.e. starting the ZigBee network) and at the same time as the “Dongle” collecting the data and reporting it to the PC tool. Next to the ZAP Coordinator you will have to build the sensor nodes that will report their data to the “Dongle”; they can be a ZAP Router or a ZAP End Device. See Section 4.1 for details on how to set the device type.

4.2.2. Available Settings

Next to the general settings in the ZAP configuration file (*zap.cfg*; see Section 4.1.2 for details) one has access to the following setting.

The time between the temperature/voltage reports can be set / changed by the following variable in the *tvsa.h* file

```
#define TVSA_DLY_ANN            60000
```

Note: The code is written such that it randomizes this value a little (to avoid collisions with other transmissions) and therefore does not give the exact same interval between reports.

4.2.3. UART Connection

If you wish to watch the information being sent to the PC in a program like the Windows communication accessory *HyperTerminal* or a COM Port Sniffer this section describes the UART Settings being used and also how these may be changed.

In case you have your own PC Tool this section will help you to identify the code you need to change to establish the link between the PC Tool and the Dongle.

Connection to Z-Sensor Monitor:

The UART setup for connecting the Dongle to the Z-Sensor Monitor [14] is shown in Figure 24 below.

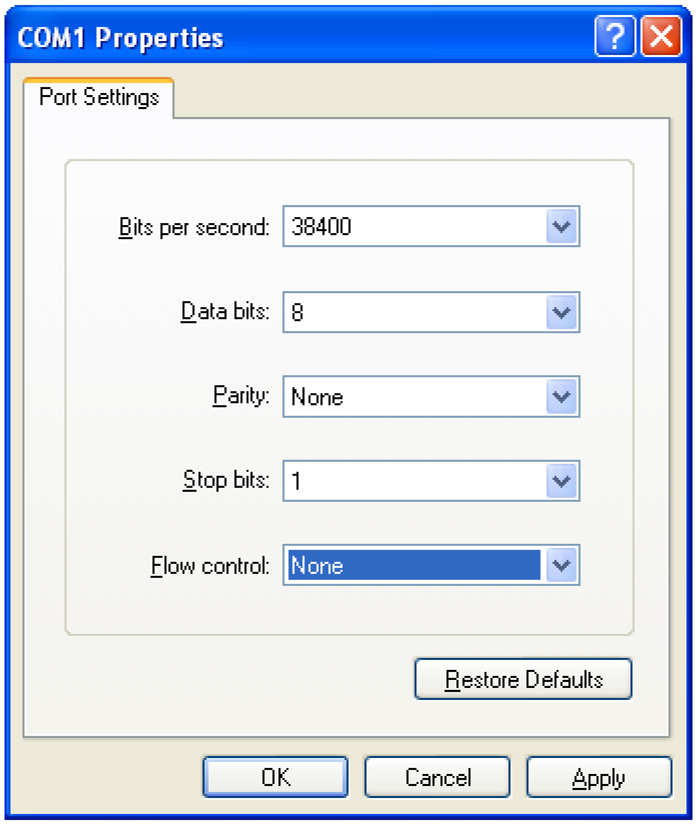


Figure 24: UART Settings used by Z-Sensor Monitor

Changing this UART Configuration to match your own PC tool is possible; however it will mean incompatibility with the Z-Sensor Monitor; hence changes should be made with caution.

The **UART settings** are set in the *tvsa.c* file using the following code:

```
halUARTCfg_t uartConfig;

uartConfig.configured = TRUE;

#ifdef TVSA_DEMO
  uartConfig.baudRate             = HAL_UART_BR_115200;
#else
  uartConfig.baudRate             = HAL_UART_BR_38400;
#endif
```



```
uartConfig.flowControl          = FALSE;
uartConfig.flowControlThreshold = 16;
uartConfig.rx.maxBufSize        = 32;
uartConfig.tx.maxBufSize        = 254;
uartConfig.idleTimeout          = 6;
uartConfig.intEnable            = TRUE;
uartConfig.callBackFunc         = tvsaUartRx;

HalUARTOpen(TVSA_PORT, &uartConfig);
```

The **HalUARTOpen function** does the following:

1) Reads in the configuration provided (see lines above regarding UART settings)
2) Configures the UART settings on the microcontroller. For example I/O port configuration, UART register configuration, UART clock source setting, etc
3) Sets baud rate
4) Sets flow control settings
5) Allocates and sets the RX and TX Buffers
6) Enables the UART interrupts
7) Clears status and other flags/buffers

To avoid invalid settings various checks are included relevant to the microcontroller; in this case an MSP430.

4.2.4. Running the example

A simple demonstration of the TVSA sample application would be to program one Dongle and at least one Router or End Device (following instructions given in the previous sections). Make sure that all devices are powered and that the Dongle is properly connected to the computer using a UART connection; details are given in the following.

Set up the Dongle first. This can be done with the following steps

1) Connect the Dongle to the PC (ensure the UART connection is there)
2) Open Z-Sensor Monitor (see Figure 25)
3) Turn Dongle On
4) Press the Play Button in the Z-Sensor Monitor (first button to the left in the top).

In case you have followed the first steps successful the Circle representing the Dongle (marked with *Sink*) should turn from grey to red color as shown in Figure 26. Then continue with the next step:

5) Turn on sensors (routers and/or end devices). Figure 27 illustrates the updated screen shot after one sensor (in this case a router) has been inserted successfully into the network.

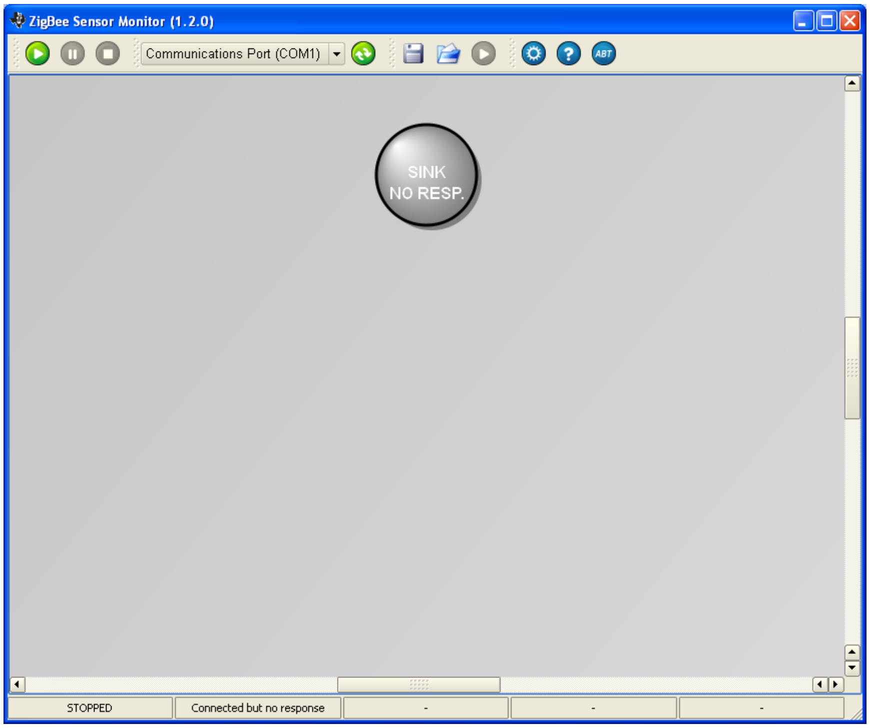


Figure 25: Screen shot from ZigBee Sensor Monitor (no dongle connected)

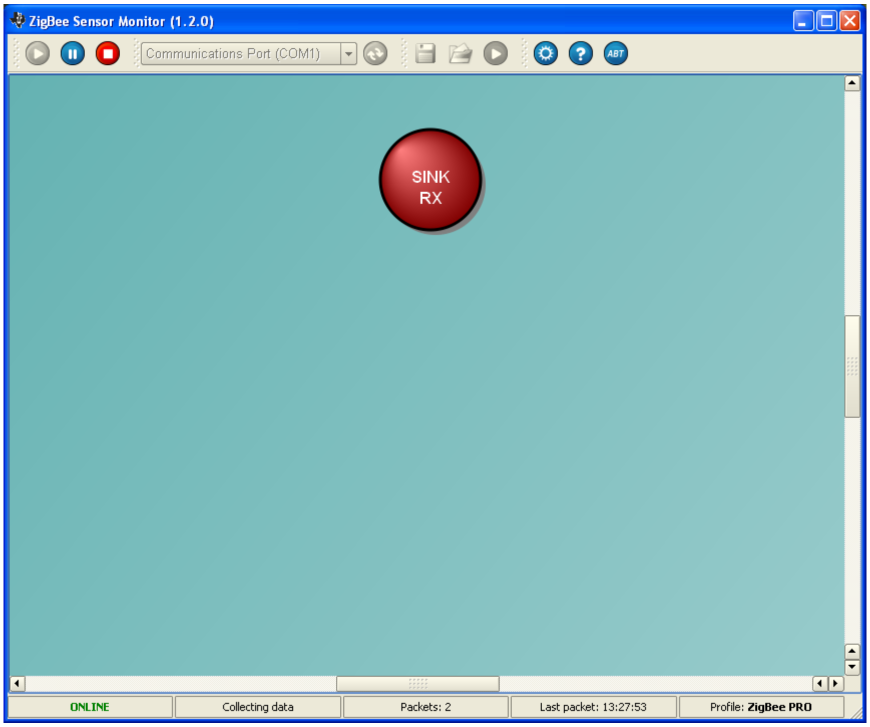


Figure 26: Screen shot from ZigBee Sensor Monitor (dongle successfully connected)

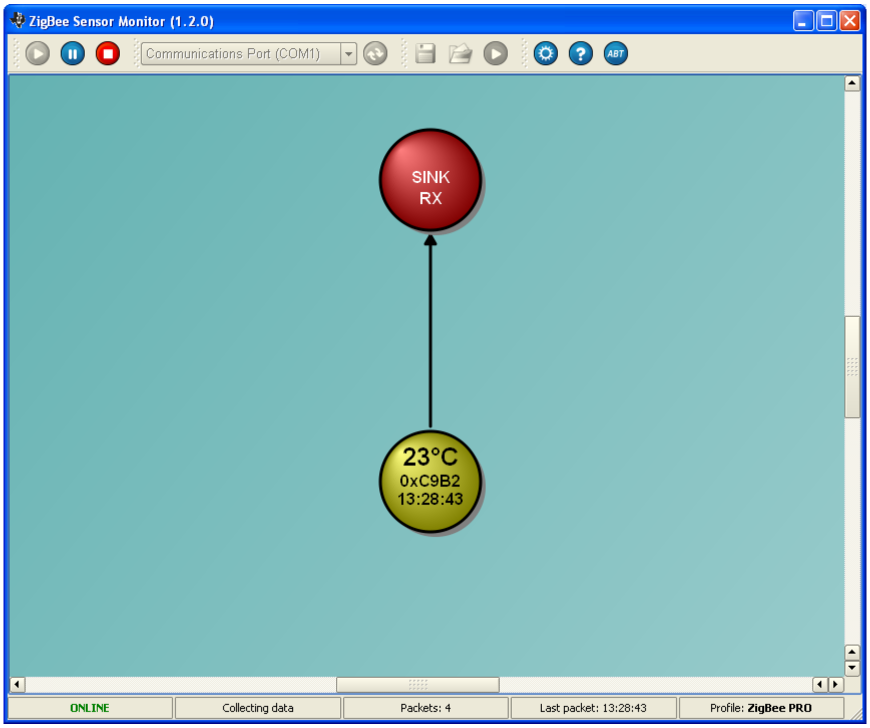


Figure 27: Screen shot from ZigBee Sensor Monitor (1 dongle + 1 sensor)

4.2.5. In Depth on the Example

In the following more details about the TVSA sample application are given.

Temperature and Voltage Measurement

If the device is not a Dongle/Coordinator, then the file *tvsa_cc2530znp.c* gets included in the build. In this file you will find the functions that calculate the temperature and voltage. These come from the ADC on the CC2530 and its usage is demonstrated in the *zapSysReq* function, retrieving ADC data using the ZNP/ZAP setup.

Note: Although there is some kind of calibration, please note that the code simply uses average values and assumes a room temperature of 22 °C.

The temperature and voltage data is entered into a data array, which is sent directly over the air in the reports to the dongle.

Over the air Packet Format

The data sent over the air is stored in a variable called *tvsaDat[]*. It is an array of 16 bytes (uint8) with the following format (for all details see the definitions in *tvsa.h*):

```
tvsaDat[0] = <Command Sent>

// TVSA Command set.
#define TVSA_CMD_DAT       0  // TVSA data message.
#define TVSA_CMD_BEG       1  // Start reporting TVSA data.
#define TVSA_CMD_END       2  // Stop reporting TVSA data.

tvsaDat[1-8] = <extended IEEE address>
tvsaDat[9] = <parent address LSB>
tvsaDat[10] = <parent address MSB>
tvsaDat[11] = <temperature data>
tvsaDat[12] = <voltage data>
tvsaDat[13] = <0x80 if router or non-dongle coordinator, otherwise for an end
device it is defined as follows> tvsaDat[13] &= (0xFF ^ 0x80);
tvsaDat[14] = 0x01 if using source routing (i.e. if TVSA_SRC_RTG), otherwise
is not explicitly defined
tvsaDat[15] =  CNF error count
```

Packet Format sent to Z-Sensor Monitor

The ping response is described in the *CC2530ZDK Sensor Demo User's Guide* [14] on page 14. Here we will simply describe the packet format sent to visualize the temperature and network data after communication with the dongle has been established.

Z-Sensor Monitor requires UART packets of the following format.
Fifteen bytes in total should be sent.

```
Packet[0]=0xFE   This is a start of frame delimiter
Packet[1]=10
Packet[2]=LO_UINT16(0x8746);  //This takes the lower 8 bits
Packet[3]=HI_UINT16(0x8746);  // This takes the higher 8 bits
Packet[4]=LO_UINT16(msg->srcAddr.addr.shortAddr);  //Lower 8 bits of the
source address
Packet[5]=HI_UINT16(msg->srcAddr.addr.shortAddr);  // Upper 8 bits of the
source address
Packet[6]=LO_UINT16(2);
Packet[7]=HI_UINT16(2);
Packet[8]=LO_UINT16(4);
Packet[9]=HI_UINT16(4);
Packet[10]= temperature data
Packet[11]=voltage data
Packet[12]=LSB of the parent devices address
Packet[13]=MSP of the parent devices address
Packet[14]=FCS Calculation on the previous 13 bytes (i.e. Packet[1] to
Packet[13])
```

4.3. Home Automation (HA) Sample Application

The ZigBee Home Automation Profile is the first public ZigBee Application Profile. The Home Automation Sample Application provides sample code to build and setup a simple ZigBee network consisting of a ZigBee HA Light and a ZigBee HA Switch. By using the joystick on the switch device the user can trigger Home Automation messages to toggle the LED (light) on the light device. It uses the ZigBee Cluster Library (ZCL) functionality of the Z-Stack, which is implemented on the ZAP side as an individual OSAL task (ZCL Task: handles incoming and outgoing ZCL messages).

The HA sample application, addressed in this section for the ZAP, is identical to the HA sample application, which is provided with the full Z-Stack installer (*ZStack-CC2530-x.x.x-x.x.x*) [6]. That installer includes several sample applications that are described in the *Z-Stack Sample Applications.pdf* document [20]. It can be found in the Z-Stack documentation folder *C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents*.

For more information about OSAL, the reader is referred to the *Z-Stack Developer's Guide.pdf* [1] and the *OSAL API.pdf* (can also be found in the Z-Stack documentation folder). Information about ZCL and its APIs can be found in *Z-Stack ZCL API.pdf*.

4.3.1. Hardware and Software setup

To setup this simple HA network, you will need a coordinator (to start the network) and another device (router or end device). The coordinator is the light and the other device (router) is the switch.

Next to the one switch additional switches can be added to the sample application; however, when adding several lights only one can be controlled by a switch, due to the simplified implemented binding process (explained in more detail in Section 4.3.3). **Remark:** The sample application can easily be modified to support a setup with several switches and lamps in different combinations; however, that is not part of this sample application as the goal is to demonstrate the ZCL communication for HA only.

First, the user has to prepare two ZNP devices (e.g. based on CC2530EM). To program the ZNP device (CC2530EM), you can use either one of the pre-built ZNP images (hex-files) or you can build your own image with a ZNP project (as described in Chapter 3).

Now that you have 2 ZNP image without security has been used that can be found in the ZNP-HexFiles folder (see Figure 21).

In the next step, build a ZAP Coordinator and a ZAP router (or ZAP end device) using the Home Automation sample applications for the ZAP. See Figure 21 for the file location and Figure 22 on how to choose the ZigBee device type. For more details on how to program the MSP430 hardware with the resulting image see Section 4.1.

Build a ZAP coordinator using the *SampleLight.eww* workspace from the *HA-SampleLight* folder for the MSP430 you have chosen (e.g. for the MSP430F2618 use *C:\Texas Instruments\ZAP-MSP430-1.0.0\Projects\zstack\ZAP\HA-SampleLight\MSP2618\SampleLight.eww*) and a ZAP router using the *SampleSwitch.eww* workspace from the *HA-SampleSwitch* folder.

After programming the corresponding MSP430 boards attach the ZNP devices (CC2530EM modules) and you are ready to run the example.

4.3.2. Running the example

To start the sample application, turn on the devices (Light/Coordinator and Switch/Router). The coordinator will start a ZigBee network and then the router will join that network.

Now, the only step remaining is to connect the switch functionality with the lamp functionality; i.e. you have to "bind" the switch to the lamp. There are many different ways in the ZigBee standard to establish this binding and how to setup a network; the whole process is referred to as commissioning. For more info the reader is referred to a good whitepaper by Daintree [21].

In Home Automation sample application can use the ZDO Match Descriptor Request to establish a binding between the switch and the light. To initiate the process, move the joystick on the switch device to the left and release. An LED on the switch should be lid to indicate that a connection, on the application level, between the switch and the lamp has been established successfully. Now, you can toggle the light (LED on the *SampleLight* application) by moving the joystick on the switch device up. The following section explains the details regarding the binding messaging and the ZigBee messages used to toggle the light.

4.3.3. In Depth on the Example

This section describes the details of the HA sample application by going through the trace shown in Figure 28 and explaining it. The trace was recorded for a coordinator based *SampleLight* and a router based *SampleSwitch* using the Ubiqua Protocol Analyzer [22].

The *Seq No* (first column) shows the sequence number of the packets received. As can be seen from the second column the application operates on channel 24, which was set using the following parameter in *zap.cfg* (see Section 4.1.2 for more details):

```
-DDEFAULT_CHANLIST=(uint32)0x01000000  // 24 - 0x18
```

The first packet (packet #1; sent at 20:58:01.519), from the coordinator device, is a beacon request to check whether there are any active networks on the channel with the intended PANID. As no replies are sent, the coordinator starts its own network. A few seconds later (at 20:58:05.367) the router sends a beacon request (packet #2), after being powered up, to check whether there is a network on this channel it can join. The coordinator replies to the beacon request with its network specific information (packet #3); coming from *MAC Src* short address

0x0000, which is always the coordinator in a ZigBee network). Users that are familiar with the standard Z-Stack sample application will notice that in this example only one single beacon request is sent out by the router before doing the association and not three (this is just an application choice and could be changed by the ZAP application designer if desired).

After sending the beacon request, the router evaluates the incoming responses according to the parameters set in *zap.cfg* (e.g. PAN ID, see Section 4.1.2) and chooses the network and parent to join. In the trace below, it chose the coordinator and sends an Association Request (packet #4) to the coordinator's MAC address 0x0000 (see *MAC Dest* field), using its own IEEE address to identify itself as can be seen from the *MAC Src* field. It uses its IEEE address (also called long address) as it has not been assigned a short address by the network yet. The coordinator acknowledges that it received it on MAC level by sending a MAC Acknowledgment (packet #5).

After sending the Association request the router sends a Data Request to query whether there is data for it at the coordinator (packet #6) expecting a response. The acknowledgment for this request, sent by the coordinator (packet #7), includes a bit indicating that there is data pending and that the data will be sent; hence, the router should wait for a packet to come. This acknowledgment is then followed by the coordinator's Association Response (packet #8), which is acknowledged again on MAC level by the router (packet #9). The Association Response contains the short address that the router got assigned by the coordinator (0x31eb); that will use from now on when communicating in the network. Furthermore, it should be mentioned that the coordinator, at the same time, identifies itself by using its own long address in the *MAC Src* field of the Association Response.

After successfully joining the network, a *DeviceAnnounce* message is broadcasted (using short address 0xffff on MAC level to reach all devices) by the router (*MAC Src* address set to 0x31eb) to the entire network. However, as this is information relevant for the coordinator and other routers in the network (i.e. not for end devices) it is send to 0xfffd on the NWK level (see *NWK Dest* field of packet #10). As a result, it will be re-broadcasted through the network by the other routers and the coordinator in the network (in this case, there is only the coordinator, packet #11).

47	10	20:20:49.295727	00:00:00.804760	18	ZigBee	MAC: Beacon Request		0xFFFF		0xFFFF	0xF4	
48	28	20:20:49.299471	00:00:00.003744	18	ZigBee	Beacon	0x3B7F		0x0000		0x47	
49	10	20:20:50.019591	00:00:00.720120	18	ZigBee	MAC: Beacon Request		0xFFFF		0xFFFF	0xF5	
50	28	20:20:50.021735	00:00:00.002144	18	ZigBee	Beacon	0x3B7F		0x0000		0x48	
51	21	20:20:50.532751	00:00:00.511016	18	ZigBee	MAC: Association Request	0xFFFF	0x3B7F	0x00124B0000000003	0x0000	0xF6	
52	5	20:20:50.533807	00:00:00.001056	18	ZigBee	Acknowledgment					0xF6	
53	18	20:20:51.028359	00:00:00.494552	18	ZigBee	MAC: Data Request		0x3B7F	0x00124B0000000003	0x0000	0xF7	
54	5	20:20:51.029319	00:00:00.000960	18	ZigBee	Acknowledgment					0xF7	
55	27	20:20:51.032231	00:00:00.002912	18	ZigBee	MAC: Association Response		0x3B7F	0x00124B0000000001	0x00124B0000000003	0xF6	
56	5	20:20:51.033479	00:00:00.001248	18	ZigBee	Acknowledgment					0xF6	
57	56	20:20:51.145631	00:00:00.112152	18	ZigBee	APS Command: Transport Key		0x3B7F	0x0000	0x1466	0xF7	0x0000
58	5	20:20:51.147807	00:00:00.002176	18	ZigBee	Acknowledgment					0xF7	
59	57	20:20:51.212727	00:00:00.064920	18	ZigBee	ZDP: Device_annce		0x3B7F	0x1466	0xFFFF	0xF8	0x1466
60	57	20:20:51.243527	00:00:00.030800	18	ZigBee	ZDP: Device_annce		0x3B7F	0x0000	0xFFFF	0xF8	0x1466
61	54	20:20:53.028199	00:00:01.784672	18	ZigBee	ZDP: Match_Desc_req		0x3B7F	0x1466	0xFFFF	0xF9	0x1466
62	54	20:20:53.057727	00:00:00.029528	18	ZigBee	ZDP: Match_Desc_req		0x3B7F	0x0000	0xFFFF	0xF9	0x1466
63	51	20:20:53.078799	00:00:00.021072	18	ZigBee	ZDP: Match_Desc_rsp		0x3B7F	0x0000	0x1466	0xFA	0x0000
64	5	20:20:53.080815	00:00:00.002016	18	ZigBee	Acknowledgment					0xFA	
65	45	20:20:53.108775	00:00:00.027960	18	ZigBee	APS Acknowledgment		0x3B7F	0x1466	0x0000	0xFA	0x1466
66	5	20:20:53.110599	00:00:00.001824	18	ZigBee	Acknowledgment					0xFA	
67	48	20:20:56.430055	00:00:03.319456	18	ZigBee	HA: On/Off		0x3B7F	0x1466	0x0000	0xFB	0x1466
68	5	20:20:56.431975	00:00:00.001920	18	ZigBee	Acknowledgment					0xFB	
69	50	20:20:56.463039	00:00:00.031064	18	ZigBee	HA: On/Off: Default response		0x3B7F	0x0000	0x1466	0xFB	0x0000
70	5	20:20:56.465023	00:00:00.001984	18	ZigBee	Acknowledgment					0xFB	
71	50	20:21:02.082799	00:00:05.617776	18	ZigBee	NWK: Link Status		0x3B7F	0x0000	0xFFFF	0xFC	0x0000
72	50	20:21:03.357511	00:00:01.274712	18	ZigBee	NWK: Link Status		0x3B7F	0x1466	0xFFFF	0xFC	0x1466

Figure 28: Screen shot from Ubiqua showing sniffer log

At this point, the router has successfully joined the network and has informed the whole network of its presence.
Remark: The alert reader will at this point notice that some packets (e.g. packet #12) are missing in the sniffer log. This is due to the fact that the NWK Link Status messages were filtered out to not confuse the reader. These are periodic messages that are sent by routers and the coordinator to monitor the link quality between them. In the sniffer logs shown in Figure 38 and Figure 39 they can be seen (marked blue).

The next packets of the trace (packet #13 - #23) are all related to the application and are triggered by user interaction.

Service discovery is performed by the switch device to match its “switch” functionality with a corresponding light device. Packet #13 is the switch device looking for a match to it’s HA Toggle clusters (ZDP Match Descriptor Request). The message was a broadcast message sent to all powered devices (0xfffd) and is rebroadcasted by 0x0000 in packet #14. The light device responds that it is a match (ZDP Match Descriptor Response) in packet #15.

In the code, the message is sent by calling the function *ZDP_MatchDescReq()* in *zcl_samplesw.c*. Every device that receives the ZDP MatchDescReq will determine if it has any end point registered with a matching application (i.e. matching input and output clusters, etc.). If there is a match, a MatchDescriptorResponse is send back (as a unicast) to the source of the request. The coordinator is a matching light device so it replies to the switch that they are compatible and could cooperate.

Note: As can be seen from the trace only unicast messages (messages send to one particular device) get acknowledged on MAC level (e.g. packet #16), while it makes no sense to acknowledge broadcast messages.

In the SampleSwitch, the information from the response is stored in the *zclSampleSw_DstAddr* variable (done in the ***case*** *Match_Desc_rsp* of the switch in the *zclSampleSw_ProcessZDOMsgs* function in *zcl_samplesw.c*) and an according APS acknowledgment message is sent to the SampleLight device (packet #17).

Note: As the goal of the sample application is only to demonstrate the HA cluster communication, the application is kept simple. As a result, only the latest destination address is saved; each SampleSwitch can only control one SampleLight, while a SampleLight can be controlled by several SampleSwitch devices.

After successfully mapping a switch to a light, the user can now toggle the light on the switch by turning/pressing the joystick on the switch up. To toggle the light, an HA compliant toggle message is sent to the light (packet #20; acknowledged by packet #21 on MAC level), the light acknowledges the receipt of the toggle command by sending the Default Response (packet #22; acknowledged by packet#23 on MAC level).

The sending of the toggle command is triggered by calling the *zclGeneral_SendOnOff_CmdToggle()* function (see function *zclSampleSw_HandleKeys()* and ***case*** *HAL_KEY_SW_1*) in *zcl_samplesw.c*.

The receipt of the toggle command on the light device is fully handled by the ZCL task, which uses the call back function (*zclSampleLight_OnOffCB()* defined in *zcl_samplelight.c*) to execute the behavior defined by the application. The light application registered for callback functions by calling *zclGeneral_RegisterCmdCallbacks()* in its initialization function *zclSampleLight_Init()* such that the ZCL task can call it each time it receives the corresponding toggle command.

For further information regarding the Home Automation sample application and the ZCL handling the reader is referred to [20].

4.4. Smart Energy Sample Application

ZigBee Smart Energy (SE) is one of the public application profiles released for the ZigBee 2007 specification. It enables utility companies and their customers to directly communicate with thermostats and other smart appliances; see www.zigbee.org for more information.

The Smart Energy Sample application, included in the MSP430 ZAP sample applications (*ZAP-MSP430-x.x.x.exe* [7]), is the optimal starting point to build your own SE application on top of Texas Instruments' CC2530 ZNP.

This section describes how to use the Smart Energy Sample Application and discusses its theory of operation. For a more general description of Smart Energy, the reader is referred to the ZigBee Smart Energy specification available from www.zigbee.org. The reader should also review the *Z-Stack Smart Energy Developer's Guide* [19] prior to using this sample application.

There are seven defined application instances within the Smart Energy Sample Application IAR project (for the location of the IAR project see Figure 21):

a. Energy Service Portal (ESP) as a Coordinator
b. Metering Device as a Router and also as an End Device
c. In Premise Display as an End Device
d. Programmable Communicating Thermostat (PCT) as an End Device
e. Load Control Device as a Router
f. Range Extender as a Router

Figure 29 shows the usage model of how these sample application instances interact with the ESP.

In the following sections detailed information is given regarding the SE sample application; the required tools (4.4.1), how to get started (4.4.3), the theory behind its operation (4.4.4), and its limitations (4.4.11).

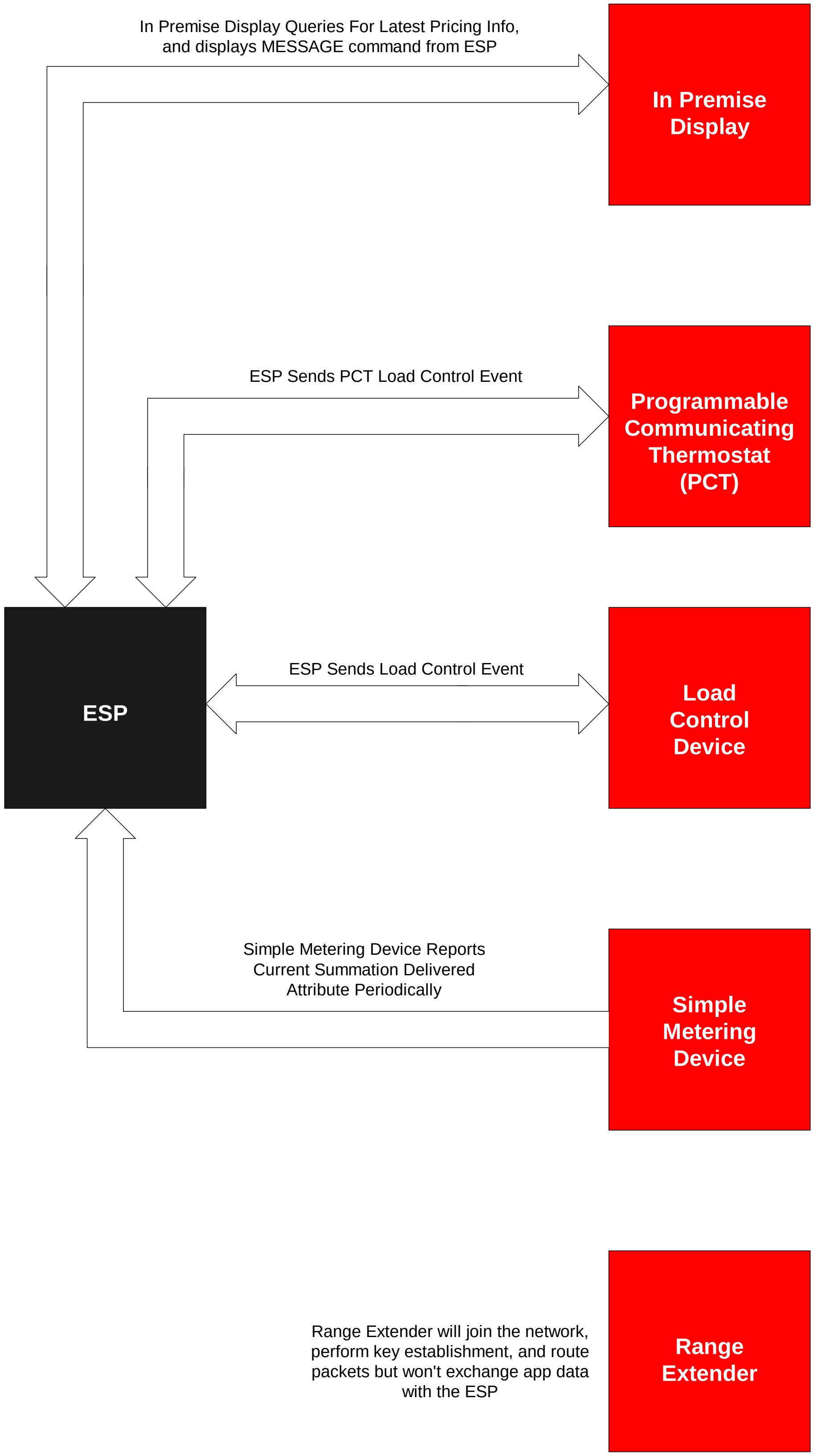


Figure 29: System Context Diagram

4.4.1. Required Tools

The tools that will be needed to evaluate this sample app and build your own application based on it are the following (see also Section 2.1):

a. IAR Embedded Workbench EW8051 [3] to build a customized ZNP image (hex-file). This is the case when targeting an image with the Certicom Library; however, if Certicom ECC security is not used, one can use the pre-built ZNP image (hex-file) customized with the correct compile options for use with the Smart Energy profile.
b. IAR Embedded Workbench EW430 [4] to build the SE sample applications that run on the MSP430.
c. SmartRF Flash Programmer Tool [5] (includes USB drivers for the SmartRF05EB board)
d. Ubiqua Protocol Analyzer from Ubilogix (*www.ubilogix.com*) or other type of network analyzer that can support Smart Energy profile decodes
e. Z-Tool 2.0 (the tool is provided as part of the Z-Stack install)
f. Z-Converter – A tool used to transform Certicom certificates data into arrays that can easily be imported into the sample applications (the tool is provided as part of the Z-Stack install)
g. Certicom ECC library if using security. Fill out their SDK license registration form at this URL: **http://www.certicom.com/index.php/component/chronocontact/?chronoformname=certicom_zigbee_sdk_registration_form.** Alternatively, you may contact TI directly to obtain a special installer that has the Certicom ECC library included.

Using Z-Converter to Transform Certicom Certificates

Z-Converter takes Certicom certificate data as input in the following format (the actual input requires no carriage returns in order for Z-Converter to process the data correctly):

IEEE Address: 00124b0000000001

CA Pub Key: 0200fde8a7f3d1084224962a4e7c54e69ac3f04da6b8

Device Implicit Cert:
0204ac2c2656f1eea4ff5dac4edda176bfe4fa70d95600124b00000000015445535453454341010900010000010910 03

Device Private Key: 00f035a9f731f265530ad5c1202562d56d1b822543

Device Public Key: 0202f71c27abfd28eb39e0b4a718ace4cf374559a6f6

This data must be entered line by line as shown above with no carriage returns into a text file. Then the user imports this data into the Z-Converter using the "*Load*" button. Z-Converter then transforms this data into an array output as follows:

IEEE Address: 0x01,0x00,0x00,0x00,0x00,0x4b,0x12,0x00

CA Pub Key: 0x02,0x00,0xfd,0xe8,0xa7,0xf3,0xd1,0x08,0x42,0x24,0x96,0x2a,0x4e,0x7c,0x54,0xe6,0x9a, 0xc3,0xf0,0x4d,0xa6,0xb8

Device Implicit Cert: 0x02,0x04,0xac,0x2c,0x26,0x56,0xf1,0xee,0xa4,0xff,0x5d,0xac,0x4e,0xdd,0xa1,0x76,0xbf, 0xe4,0xfa,0x70,0xd9,0x56,0x00,0x12,0x4b,0x00,0x00,0x00,0x00,0x01,0x54,0x45,0x53,0x54, 0x53,0x45,0x43,0x41,0x01,0x09,0x00,0x01,0x00,0x00,0x01,0x09,0x10,0x03

Device Private Key: 0x00,0xf0,0x35,0xa9,0xf7,0x31,0xf2,0x65,0x53,0x0a,0xd5,0xc1,0x20,0x25,0x62,0xd5,0x6d, 0x1b,0x82,0x25,0x43

Device Public Key:
0x02,0x02,0xf7,0x1c,0x27,0xab,0xfd,0x28,0xeb,0x39,0xe0,0xb4,0xa7,0x18,0xac,0xe4,0xcf,0x37,0x45,0x59,0xa6,0xf6

Note that the Device Public Key is not used as part of the input into the Certicom library but is provided for completeness.

The user then copies these values into the zap_certs.c application file as such:

```
const uint8 seIEEE[] = {
  0x01, 0x00, 0x00, 0x00, 0x00, 0x4b, 0x12, 0x00
};
const uint8 seData0x69[] = {
  0x03, 0x07, 0x8c, 0x45, 0xde, 0xa5, 0x06, 0xd0,
  0x7f, 0x1b, 0x82, 0x21, 0x22, 0xb5, 0xa3, 0x1e,
  0xb0, 0xa0, 0xd6, 0x29, 0x55, 0xdb, 0x00, 0x12,
  0x4b, 0x00, 0x00, 0x00, 0x00, 0x01, 0x54, 0x45,
  0x53, 0x54, 0x53, 0x45, 0x43, 0x41, 0x01, 0x09,
  0x00, 0x08, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00
};
const uint8 seData0x6A[] = {
  0x02, 0x28, 0x4a, 0x56, 0x3f, 0x02, 0xf2, 0xc8,
  0xbd, 0xa7, 0x57, 0xf9, 0x61, 0xbb, 0x8c, 0xb4,
  0xfb, 0x6e, 0x90, 0xed, 0x42
};
const uint8 seData0x6B[] = {
  0x02, 0x00, 0xfd, 0xe8, 0xa7, 0xf3, 0xd1, 0x08,
  0x42, 0x24, 0x96, 0x2a, 0x4e, 0x7c, 0x54, 0xe6,
  0x9a, 0xc3, 0xf0, 0x4d, 0xa6, 0xb8
};
```

The mapping of the labels from the Certicom certificate to the variables in the sample application is as follows:

```
IEEE → seIEEE[]
Device Implicit Cert → seData0x69[]
Device Private Key → seData0x6A[]
CA Pub Key → seData0x6B[]
```

Figure 30 provides a screenshot of the Z-Converter graphical interface. The user can also save the output into a text file for later use using the “*Save As*” button.

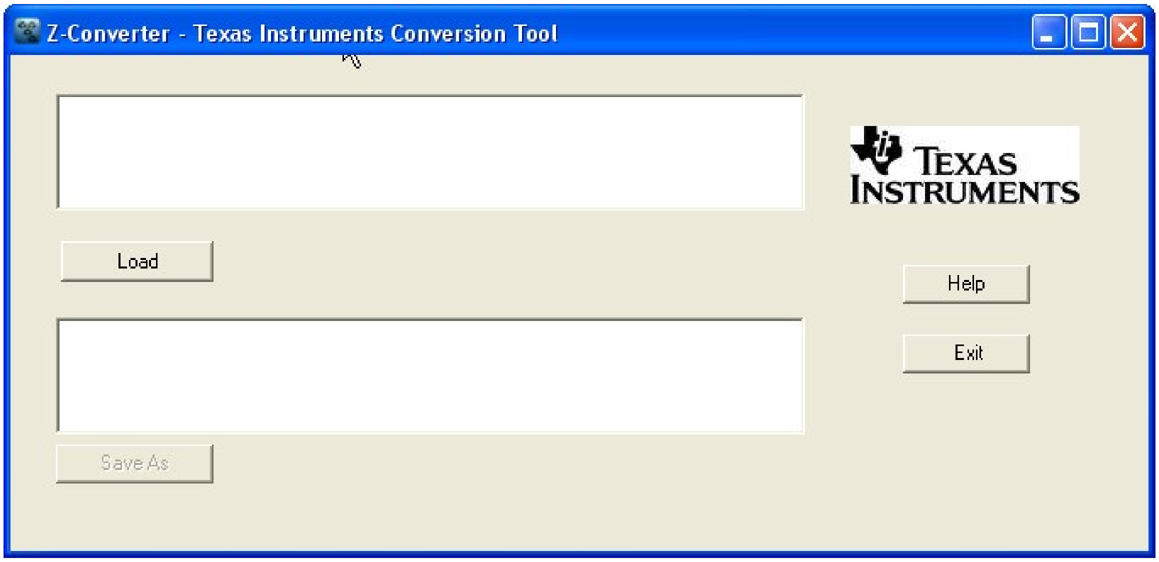


Figure 30: Z-Converter Graphical Interface

Upon initialization, the sample application will then initialize these certificates into the non-volatile memory section of the CC2530 based ZNP as shown below:

```
// Program the necessary certificate data (done in Z-Stack apps by Z-Tool).
    (void)znp_nv_write(ZCD_NV_lOCAL_CERTIFICATE,  0, sizeof(seData0x69), (uint8 *)seData0x69);
    (void)znp_nv_write(ZCD_NV_STATIC_PRIVATE_KEY, 0, sizeof(seData0x6A), (uint8 *)seData0x6A);
    (void)znp_nv_write(ZCD_NV_CA_PUBLIC_KEY,      0, sizeof(seData0x6B), (uint8 *)seData0x6B);
```

4.4.2. Configuring Certicom Keys for Production Devices

The previous section discussed a method for configuring Certicom keys from the host processor. This works well for the development phase, but for production, a different solution is often desired to help streamline the manufacturing process. For this reason, and also for enhanced security, Z-stack provides an option to store the Certicom keys in the lock bits page of the CC2530. This is also the recommended option as the CC2530 has a lock bit to lock the debug interface port.

On the CC2530, the last available page of flash is used. Figure 31 shows the memory map of the lock bits page.

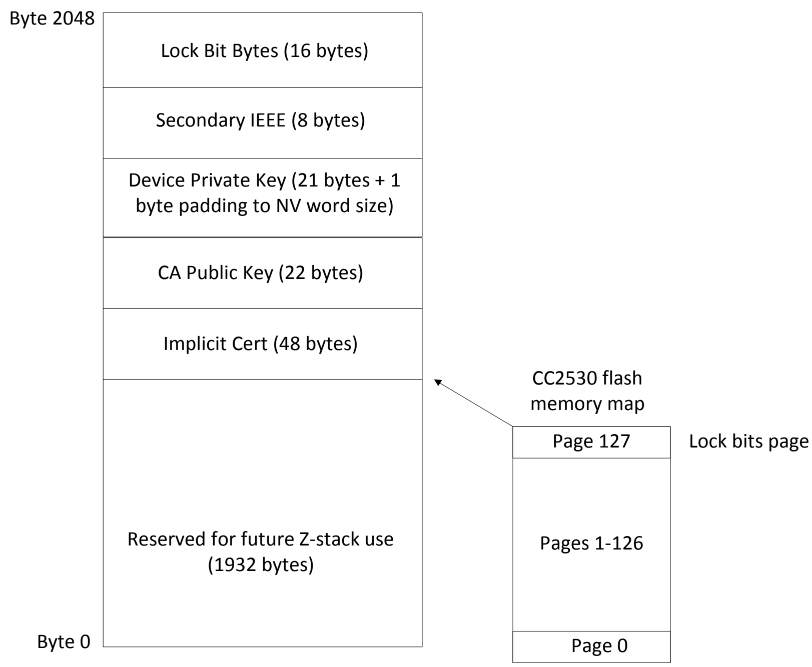


Figure 31: Memory map of lock bits page

For the CC2530, the console version of the SmartRF Flash Programmer has been updated (since ver 1.8) to provide a command line interface that is able to program the lock bits page with the certificate data. The console program accepts a .hex file along with the certificate data in .txt format.

The procedure to generate the .hex file is discussed in section 3.2.

At the command line prompt, the following syntax should be used:

SmartRFProgConsole S EPV “F= <path to hex file>” EKF=”<path to certificate file.txt>”

The format of the certificate should be as follows:

IEEE Address: 00124b0000000003
CA Pub Key: 0200fde8a7f3d1084224962a4e7c54e69ac3f04da6b8
Device Implicit Cert:
0204ac2c2656f1eea4ff5dac4edda176bfe4fa70d95600124b0000000003544553545345434101090
001000001091003
Device Private Key: 034bc37a7210b7407a51dc11e5aebaf2e1503f6955
Device Public Key: 020718021c2ce9c58d2ad8352ab9ff452ff1c3bdadb3

Note: *The data for the device implicit cert should be on one line (i.e. no carriage return separations should be included).*

The .hex image would then be programmed into the CC2530 using the SmartRF Flash Programmer tool at the same time the lock bits page is programmed with the certificate data in the .txt file. The screenshot below shows an example.

```
C:\Program Files\Texas Instruments\SmartRF Flash Programmer>SmartRFProgConsole S
 EPV "F=C:\Program Files\Texas Instruments\SmartRF Flash Programmer\rangeext.hex
" EKF="c:\cert3.txt"

Texas Instruments SmartRF Flash Programmer v1.8.1
-------------------------------------------------

0295: Erasing entire flash...
0295: Programming flash.............................................
0295: Verifying flash (bytewise check)..................................
...................................................
0295: Erase, program and verify OK
```

There are also several functions in the console version that can be used to create a very flexible script. First, note the 'x' option, that will list all available EBs. Example:

C:\Program Files\Texas Instruments\SmartRF Flash Programmer>SmartRFProgConsole.exe x

Texas Instruments SmartRF Flash Programmer

Device:SmartRF05EB ID:2769 (fwId:0500, fwRev:0013) Chip:CC2530
Device:SmartRF05EB ID:7335 (fwId:0500, fwRev:0013) Chip:CC2530

One can then write a batch script (or similar) with the following lines:

SmartRFProgConsole.exe S(2769) EPV F="hex_image.hex" EKF="certificate_data_1.txt"
SmartRFProgConsole.exe S(7335) EPV F="hex_image.hex" EKF="certificate_data_2.txt"

This example assumes that the path of the .hex image and the certificate data .txt file are in the same directory as the SmartRFProgConsole.exe.

4.4.3. Getting Started

This section explains how to get started with the SE sample application.

Building the ESP and Simple Meter Application Instances

The SE sample application project is located in *C:\Texas Instruments\ZAP-MSP430-1.0.0\Projects\zstack\ZAP\SE-SampleApp\<Target>* (e.g. *<Target>* = EXP5438); see also Figure 21. The following steps explain how to build ESP and Simple Meter Application Instances.

Start by opening the *SampleApp.eww* project file. The figures below (Figure 32 and Figure 33) show how each configuration is organized. For each device configuration, only the relevant application files are brought in for each device configuration.

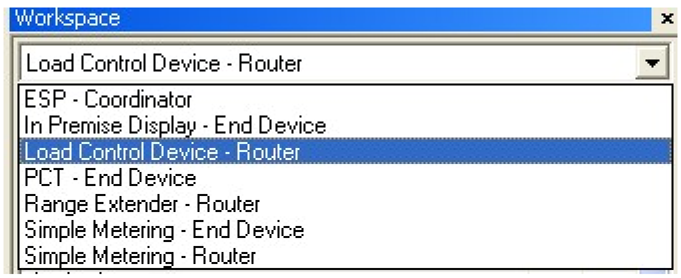


Figure 32: SE sample application workspace options

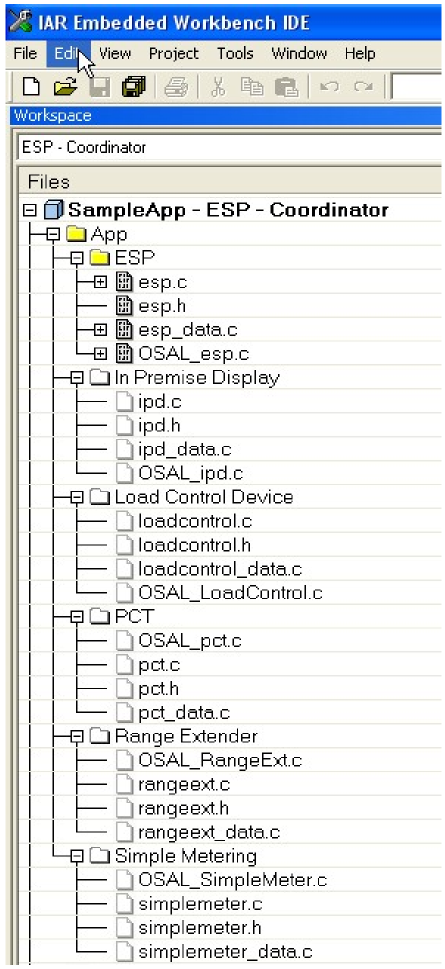


Figure 33: SE sample application workspace setup for ESP

Then build the "*ESP – Coordinator*" and "*Simple Meter – Router*" configurations:

1. Using Certicom ECC security requires that the CC2530 ZNP image (hex-file) is built with the SECURE=1 compile option. Before rebuilding the ZNP image, take the Certicom library and rename it to ecc.r51 and drop it into *C:\Texas Instruments\ZStack-2.3.1-1.4.0\Projects\zstack\Libraries\TI2530DB\bin*
2. Typically, the NWK_INDIRECT_MSG_TIMEOUT parameter of the ZNP image (in the *f8wConfig.cfg* file) must be increased to a suggested value of 10 in order to buffer the message long enough to accommodate the 8 second poll period by the end device. The MAX_POLL_FAILURE_RETRIES parameter should also be set to 4 as during the CBKE procedure the ESP will be somewhat unresponsive to data requests during this time.
3. When building the ZNP image (in addition to point 2 above), ensure the following compile options are set as follows in the *znp.cfg* file (located in *C:\Texas Instruments\ZStack-2.3.1-1.4.0\Projects\zstack\Tools\CC2530DB*):

-INTER_PAN
-DHOLD_AUTO_START
-DNV_RESTORE
-DNV_INIT
-SE_PROFILE
-ZNP_ZCL
-DMT_APP_FUNC
-DSECURE=1 (ONLY if using Certicom ECC security – otherwise set to 0)

4. When building the ZAP sample application project, ensure the following compile options are set as follows in the *zap.cfg* file (located in *C:\Texas Instruments\ZAP-MSP430-1.0.0\Projects\zstack\ZAP\Source*):

   -DZAP_AUTO_CFG=TRUE
   -DZAP_AUTO_START=TRUE
   -DZAP_NV_RESTORE=FALSE
   -DSECURE=1 (ONLY if using Certicom ECC security – otherwise set to 0)
   -DZAP_ZNP_MT=TRUE (ONLY set to TRUE if using Certicom ECC security)
   -DZDAPP_CONFIG_PAN_ID and -DDEFAULT_CHANLIST should be set to the appropriate values.

5. Highlight the configuration desired (Figure 32) and go to *Project* → *Options* and select the "Erase main and information memory" as shown in Figure 34. Then build the program via *Project* → *Rebuild All*.

6. Download the program by clicking on the debug icon or by going to Project -> Debug. Hit the Run button, and watch the coordinator start up, or if it's a device, it will try to join the network automatically. The IEEE address of the device and the PAN ID of the network will be displayed on the LCD.

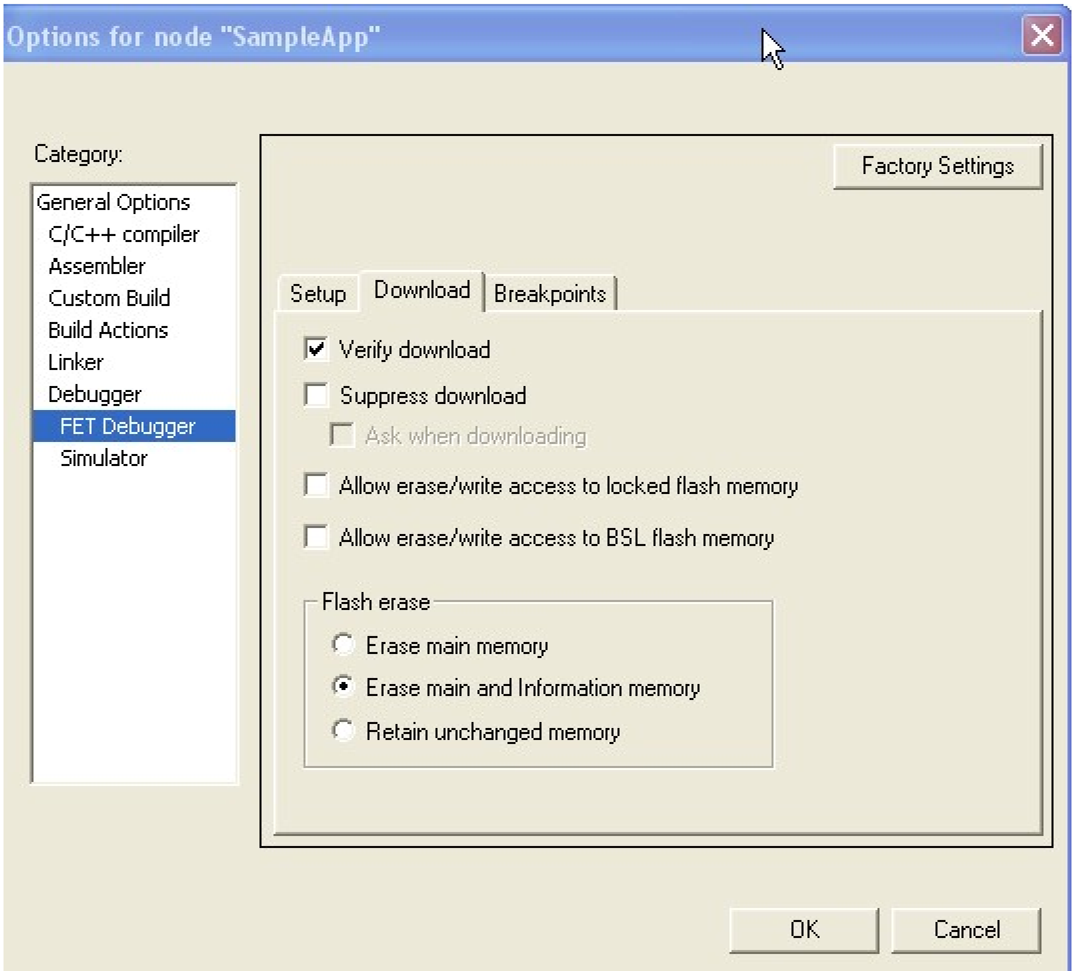


Figure 34: Project options (FET Debugger) for SE Sample Applications

Extracting Established Application Link Keys Using Z-Tool

One must use the Z-Tool program supplied with the Z-Stack installer to retrieve the established link key pairs for each device connected to the ESP. Open Z-Tool from the Texas Instruments start menu links and select *Tools* → *Settings* to configure the baud rate, Port Alias, and Handshake protocol as shown below in Figure 35.

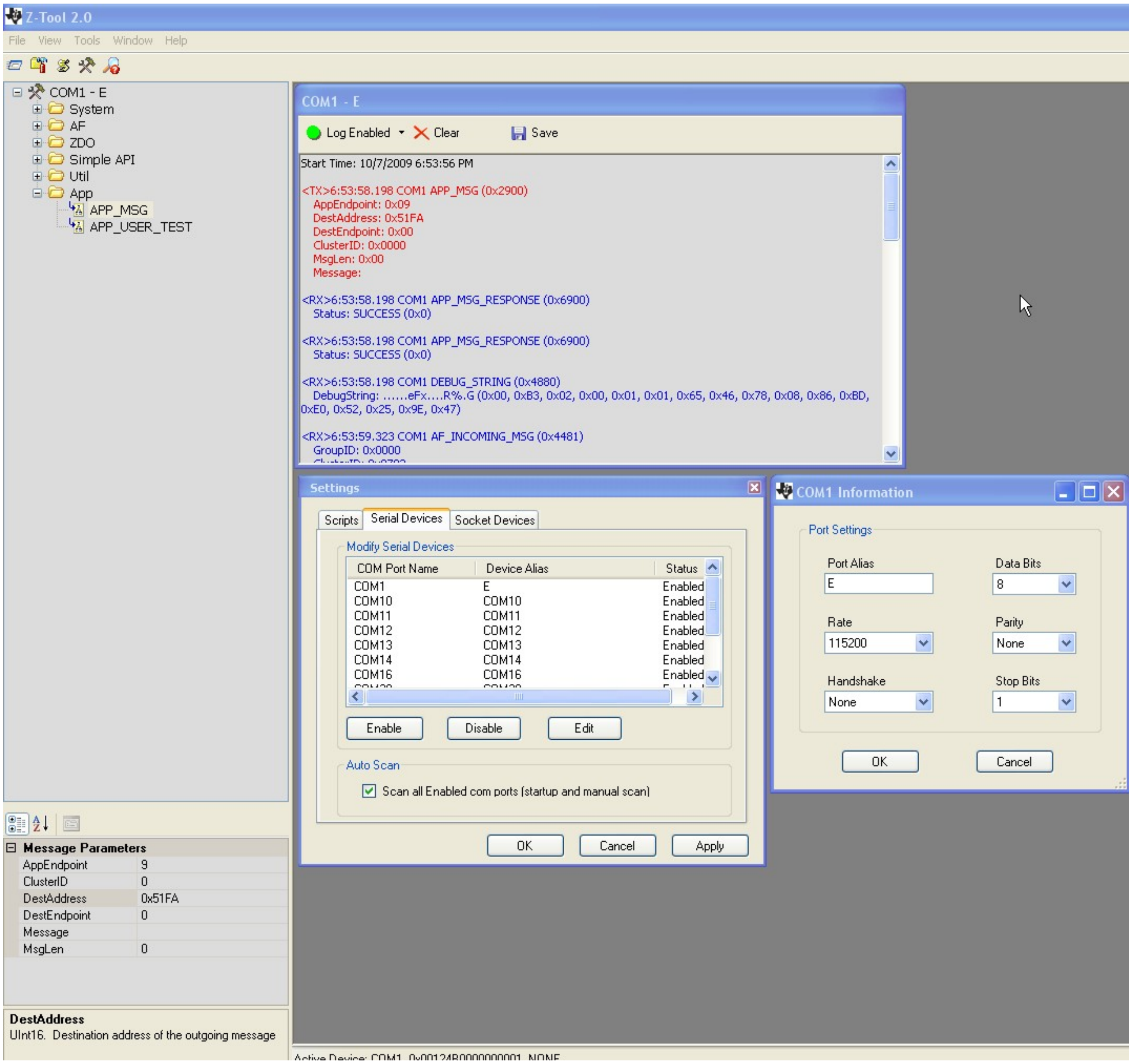


Figure 35: Screen shot from Z-Tool showing the settings window to set COM1 settings

Once key establishment is successful, use the ZDO_GET_LINK_KEY command to extract the link key established for the device. This can be run on any of the pair of devices in order to get the key (needed for the packet sniffer as described below). Configure the ZDO_GET_LINK_KEY command as shown below in Figure 36. The only value that changes is the IEEE Address of the partner device.

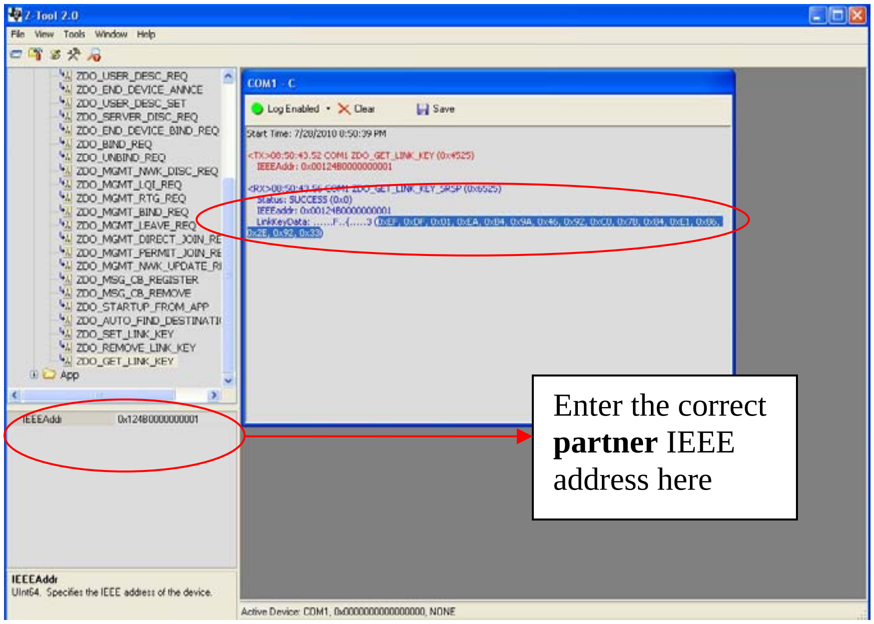


Figure 36: Settings for sending the ZDO_GET_LINK_KEY message

Copy and paste the key into Ubiqua. To get to the menu for entering the Security Key as shown in Figure 37 go to the *Tools* → *Options…* then select the Keys tab and double-click on the key you want to modify or add a new key by pressing the add button.

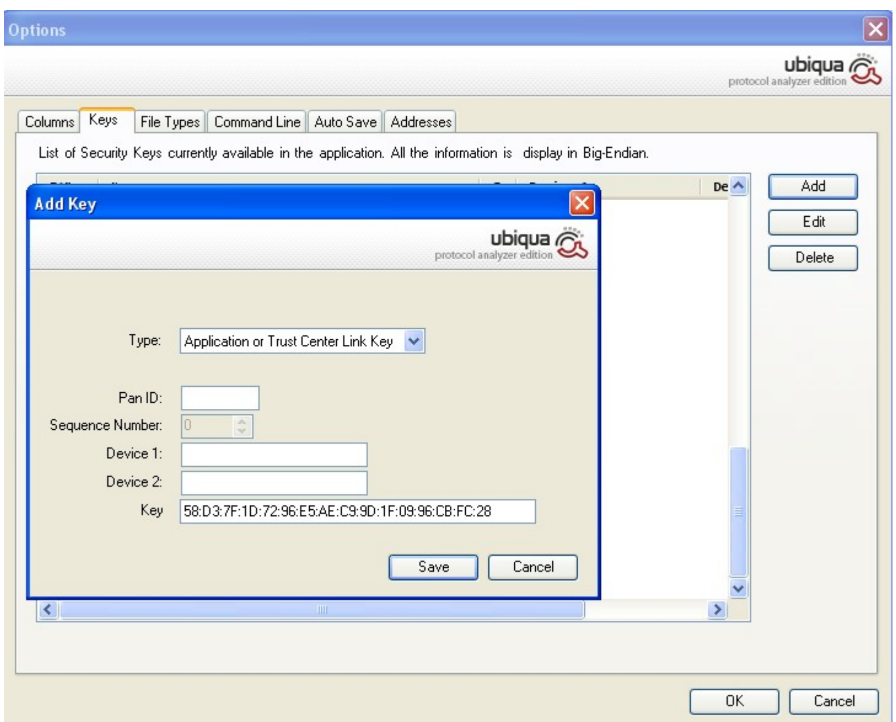


Figure 37: Screen shot from Ubiqua Protocol Analyzer (security settings)

Running the ESP and Simple Meter Applications

After compiling the sample app instances (as described above) and programming the devices one can start the applications as follows:

1. Power the coordinator, wait for "*ZigBee Coord*" to show up on the LCD display. The next line of the LCD will display the PAN ID of the established network.
2. Then power the Simple Meter device. If using Certicom ECC security, verify with the sniffer that key establishment is complete. If the Simple Meter device is configured as an end device, its polling rate is set to 8secs. Therefore the key establishment procedure takes a lot longer. Wait about 20 seconds for this to complete. Verify with the sniffer that the end device received the confirm key response. Once the key establishment procedure is completed, the Simple Meter device will start sending attribute reports to the ESP, and the ESP will display the current summation delivered value on its LCD.

Note: The compile option NV_RESTORE is **not** turned on by default on the ZAP, so if you power cycle any of the devices, it needs to go through the key establishment procedure again, and a different link key would be used. NV_RESTORE is turned off by default to allow rapid development. Also, any device joining the ESP wouldn't be able to join more than once since the new link key is used for authenticating the device instead of the default TC link key. Power cycle the ESP and then the joining device so that it is able to join using the default TC link key.

Figure 38 and Figure 39 show what happens in the Ubiqua Protocol Analyzer for these two application instances (with Certicom ECC security in use).

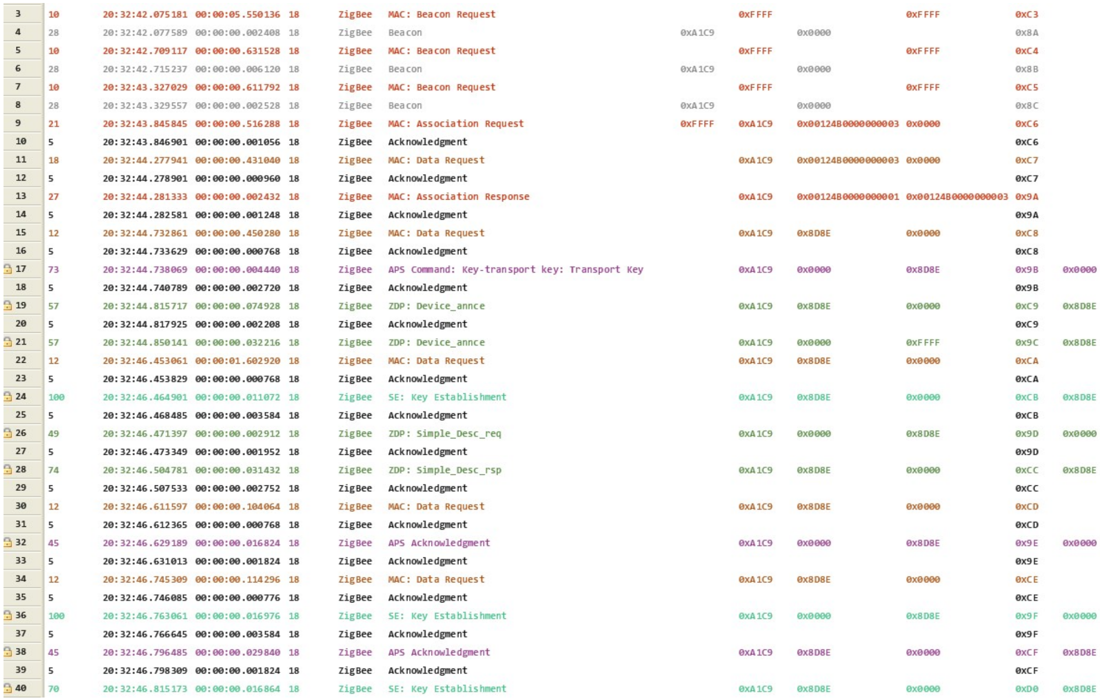


Figure 38: Screen shot from Ubiqua (start up – part 1)

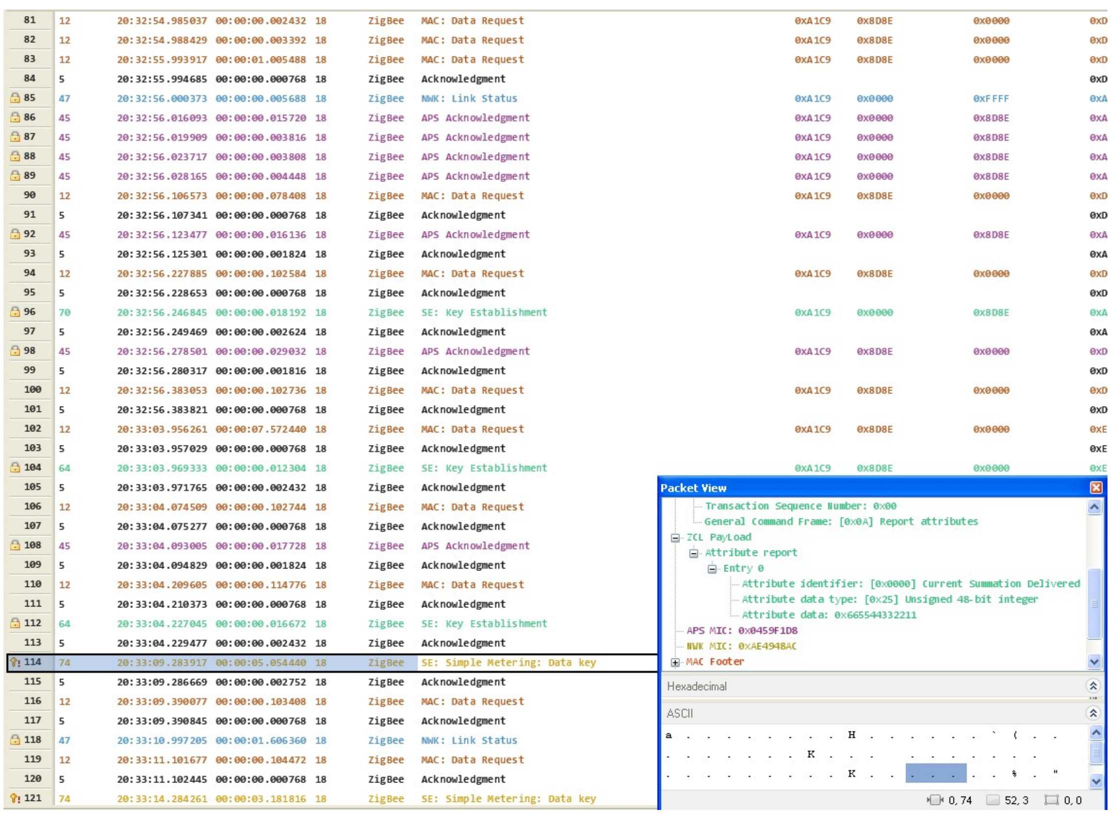


Figure 39: Screen shot from Ubiqua (start up – part 2)

4.4.4. Theory of Operation

This section explains how each application instance behaves with respect to the ESP device and also discusses the design of each application instance.

SE Secure Joining

The default trust center link key (TC link key) is used to commission each device. Each device uses the SE secure joining process. See the Z-stack Smart Energy Developer's Guide [19] for more details.

Key Establishment

Upon successfully joining the network using security, each device will initiate key establishment with the ESP. Certificate information required to perform the key establishment is entered in ahead of time as part of the sample app initialization. Figure 40 shows a flowchart of the device startup logic. The ZDO_STATE_CHANGE event is an OSAL system message that is provided to the application to indicate that the device has successfully started or joined the network.

Device and Service Discovery

Each device communicates with the ESP. Since the ESP is the coordinator and will always have a short address of 0x0000, devices that join the network can assume this and communicate with the ESP directly. Therefore, no device discovery or service discovery is required for joining devices. The ESP however, demonstrates the ability to discover Load Control devices and PCTs. Once the device joins the network and performs a successful key establishment, it starts its communications with the ESP based on the application behavior.

The following sections (4.4.5-4.4.10) define the application behavior for each device after it has successfully joined the network using SE secure join, and has an application link key established with the ESP.

4.4.5. ESP

The ESP is assumed to be the coordinator, trust center, and network manager of the network. Every other device communicates with the ESP.

The ESP application instance consists of the following modules:

OSAL_esp.c – functions and tables for task initialization
esp.c – main application function that has init and event loop function
esp.h – header file for application module
esp_data.c – container for declaration of attributes, clusters, simple descriptor

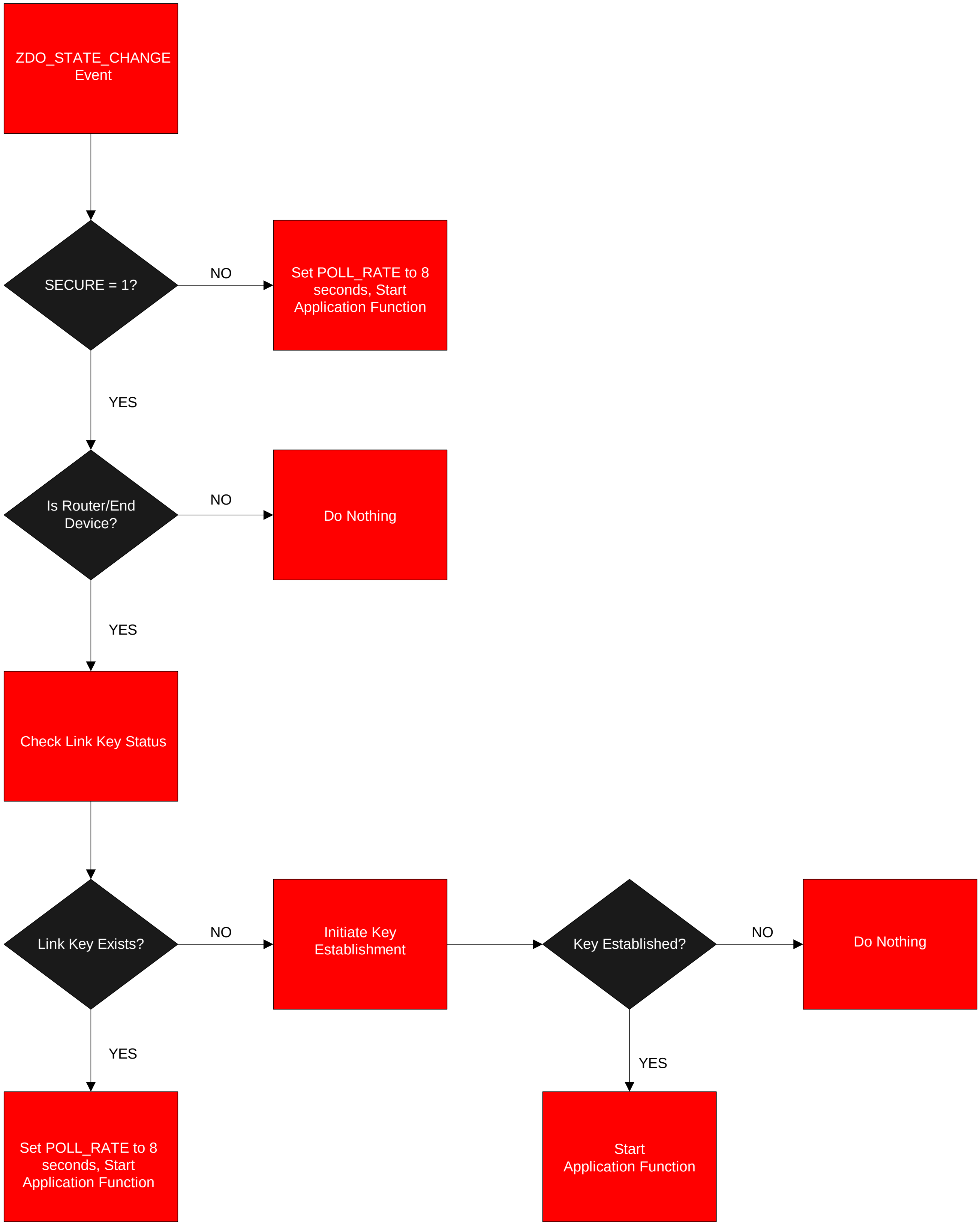


Figure 40: Flowchart of Device Startup Logic

The ESP application makes function calls to the following ZCL SE functions and ZDO API functions:

esp_GetCurrentPriceCB – callback executed when get current price message is received either via unicast or INTER-PAN.

zclSE_Pricing_Send_PublishPrice – send publish price command to IPD either via unicast or INTER-PAN.

esp_ProcessInReportCmd – print out value of current summation delivered when attribute report is received

zclSE_LoadControl_Send_LoadControlEvent – send a load control event message to a load control device

zclSE_Message_Send_DisplayMessage – send a message command to an IPD

esp_ProcessAppMsg – MT_SYS_APP_MSG can be used to tunnel any application specific messages into the device via UART (e.g. by using Z-Tool). It is left as a hook so the application developer can fill in the necessary functionality.

esp_ProcessZDOMsg – responses for end device announce and simple descriptor requests are processed here. When an end device announce message is received, the SIMPLE_DESC_QUERY_EVT event is set, and this causes the simple descriptor request to be triggered for this source address.

esp_HandleKeys – user switch events are processed here. SW1 sends out a load control event to the PCT, SW2 sends out a load control event to the load control device, SW3 sends out a display message command to the IPD.

The ESP interacts with other application instances in different ways. Endpoints, command structures, ZDO callbacks, and SE callbacks are initialized by calling *esp_Init*. System and user events are handled in *esp_event_loop*.

When a Simple Metering device joins the network, once the key establishment procedure is successful, it will receive attribute reports from the Simple Metering device every 5 seconds. Therefore, every 5 seconds the function *esp_ProcessInReportCmd* is called to display the received *CurrentSummationDelivered* attribute on the ESP's LCD screen.

When an IPD device joins the network, once the key establishment procedure is successful, it will send a get pricing info message. On the ESP, the *esp_GetCurrentPriceCB* is called when the get pricing info message is received. This then calls *zclSE_Pricing_Send_PublishPrice* to send out the publish price command to the IPD. If SW3 is pressed, the function *zclSE_Message_Send_DisplayMessage* is called to send a display MESSAGE to the IPD device.

When a PCT or Load Control device joins the network and establishes a link key with the ESP, the ESP will discover these devices by using the end device announce to trigger a simple descriptor ZDO request. Each simple descriptor response is parsed in the ZDO callback handler *esp_ProcessZDOMsg*, and the device ID field is checked to determine whether this response came from the PCT or Load Control Device. Depending on the device ID, the destination address for the PCT or Load Control Device is then populated. This is how the ESP then knows which type of load control event to send to which device. SW1 is used to send a PCT event to the PCT, and SW2 is used to send an event to the load control device.

4.4.6. Simple Metering Device

The Simple Metering Device will periodically send reports for the *CurrentSummationDelivered* Simple Metering attribute to the ESP. The ESP will display the *CurrentSummationDelivered* value on the LCD. See Figure 41 for a sequence diagram.
The Simple Meter application instance consists of the following modules:

OSAL_simplemeter.c - functions and tables for task initialization
simplemeter.c – main application function that has init and event loop function
simplemeter.h – header file for application module
simplemeter_data.c – container for declaration of attributes, clusters, simple descriptor

The Simple Meter application makes the following function calls:

zcl_SendReportCmd – this function sends the *CurrentSummationDelivered* report attribute to the ESP.

simplemeter_HandleKeys – user switch events are processed here.

Once the simple meter device joins the network, it goes through the state machine explained in Figure 41. *simplemeter_KeyEstablish_ReturnLinkKey* is called to check if a link key has already been established with the ESP. If it hasn't, it will set the osal event SIMPLEMETER_KEY_ESTABLISHMENT_REQUEST_EVT. The event handler for this in the process event loop will then call *zclGeneral_KeyEstablish_InitiateKeyEstablishment* to do the CBKE procedure. Upon its success, the application will receive a ZCL_KEY_ESTABLISH_IND system message. An osal timer event called SIMPLEMETER_REPORT_ATTRIBUTE_EVT is then started to send attribute reports every 5 seconds of the *CurrentSummationDelivered* attribute. The structure for the report command is created and initialization of the attribute is done in the *simplemeter_Init* function.

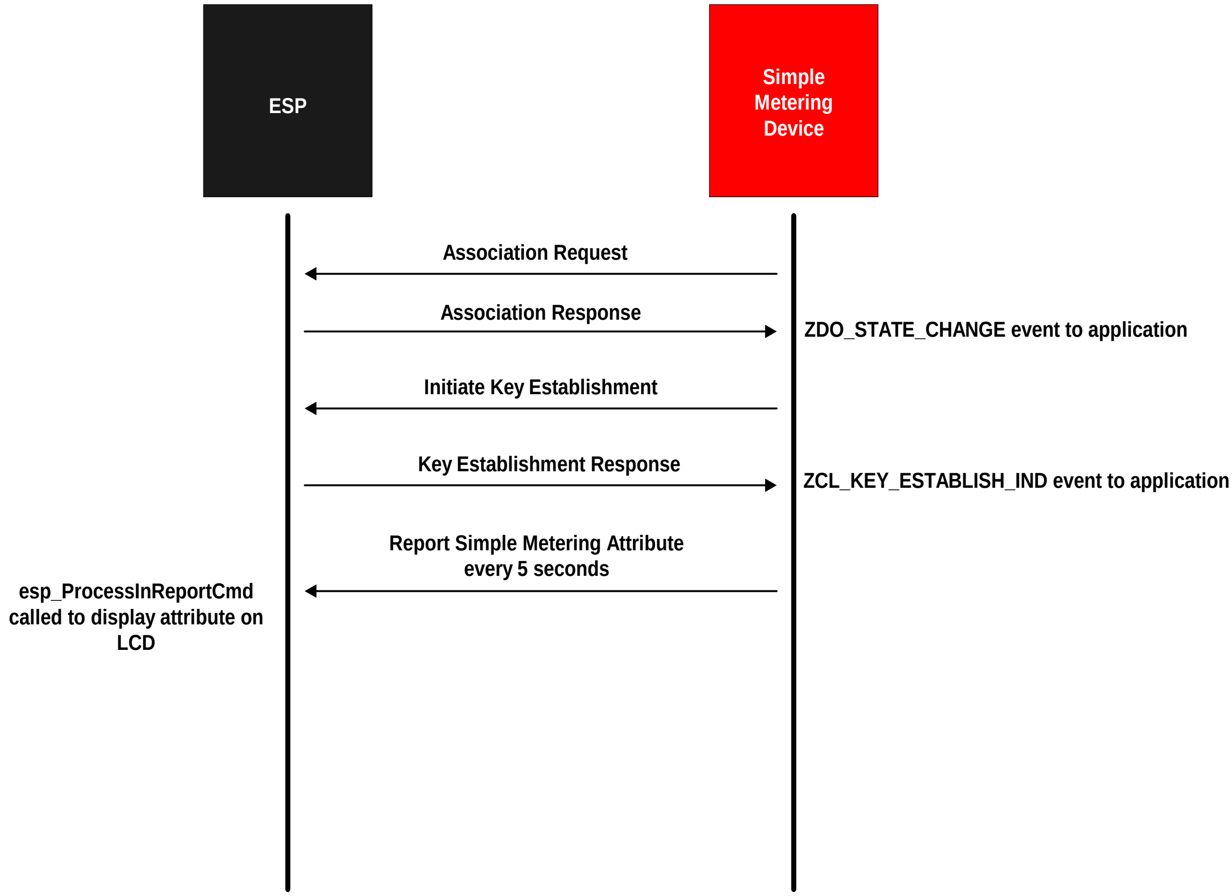


Figure 41: Sequence Diagram for a Simple Meter Device

4.4.7. Load Control Device

The ESP will send a load control event to the Load Control Device via a user switch button press. In the Load Control Event payload, the Device Class Field Bitmap will indicate that Bit 7 is set (representing Residential ON/OFF Load). When the Load Control Device receives the load control event, it sends a *ReportEventStatus* command that it received it, and sends another one when it starts it. The Start Time field will indicate to “Start Now”. The event duration will last 1 minute. While the load control event is in process, the Load Control Device will flash its LED. When the load control event is finished, another *ReportEventStatus* command will be sent to the ESP to indicate the completion of the load control event. See Figure 42 for a sequence diagram.

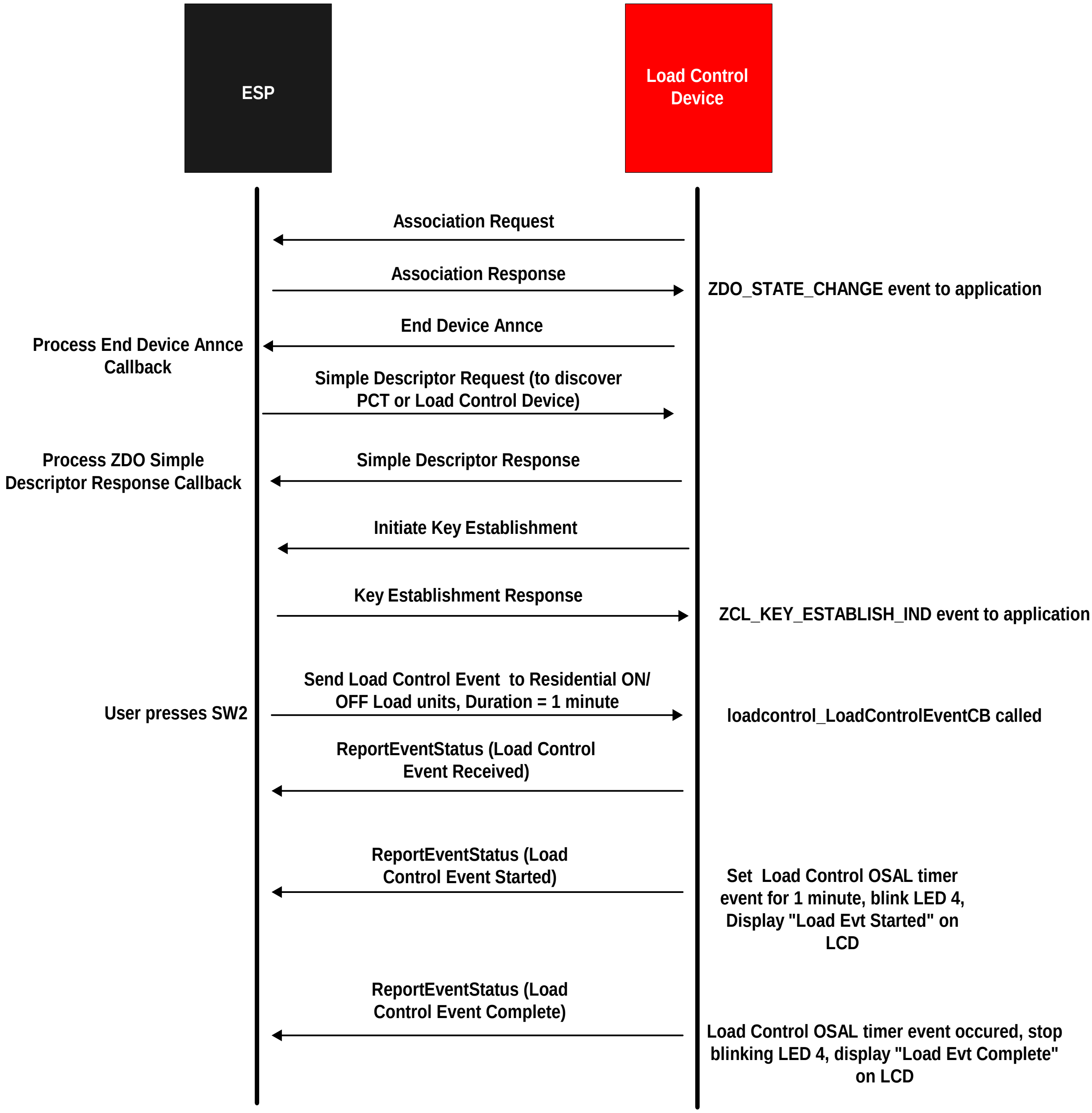


Figure 42: Sequence Diagram for a Load Control Device

The Load Control Device application instance consists of the following modules:

OSAL_loadcontrol.c - functions and tables for task initialization
loadcontrol.c – main application function that has init and event loop function
loadcontrol.h – header file for application module
loadcontrol_data.c – container for declaration of attributes, clusters, simple descriptor

The Load Control application makes function calls to the following ZCL SE functions and ZDO API functions:

loadcontrol_LoadControlEventCB – this function is called when the load control device received a load control command.

zclSE_LoadControl_Send_ReportEventStatus – When a load control command is received, the device sends a report event status command back to the ESP. Possible values for the event type for this particular sample app could be event received, event started, and event completed. The response structure (rsp) is made a global variable so that the process event loop can manipulate the eventStatus field once the load control event is complete.

loadcontrol_HandleKeys – user switch events are processed here.

Once the Load Control device joins the network, it goes through the state machine explained in Figure 42. The function *loadcontrol_KeyEstablish_ReturnLinkKey* is called to check if a link key has already been established with the ESP. If it hasn't, it will set the osal event LOADCONTROL_KEY_ESTABLISHMENT_REQUEST_EVT. The event handler for this in the process event loop will then call *zclGeneral_KeyEstablish_InitiateKeyEstablishment* to do the CBKE procedure. Upon its success, the application will receive a ZCL_KEY_ESTABLISH_IND system message. Nothing is done at this point, and the load control device is ready to accept load control messages from the ESP.

When a load control command is received, the callback *loadcontrol_LoadControlEventCB* is executed. This callback function checks the issuer event id (0x12345678), the start time (0x00000000 = NOW) in order to make sure that it is not just blindly responding to a random load control event. Furthermore, it checks the *deviceGroupClass* to determine whether this load control event was for the PCT or load control device. The values within this load control command originate from the ESP. The correct string on the LCD is then displayed to indicate whether this is a load control device event or PCT event. It is assumed that the load control device belongs to the residential on/off load device class, and that the PCT belongs to the HVAC compressor/furnace device class.
An osal timer event called LOADCONTROL_LOAD_CTRL_EVT is then started to commence the load control event and flash the LED for the duration specified, which is 1 minute. When this timer event expires, the status response of event completed is sent back to the ESP, and the LED stops flashing. The user also sees a display on the LCD indicating that the load control event is complete.

4.4.8. PCT

The PCT will have a very similar behavior to the Load Control Device. However, in the Load Control Event payload, the Device Class Field BitMap will indicate that Bit 0 is set (HVAC compressor or furnace). The Load Control Event for the PCT will be regarded as a “PCT Event”, and the message “PCT Event Started” will be displayed if the device has LCD support. See Figure 43 for a sequence diagram.

The PCT application instance consists of the following modules:

OSAL_pct.c - functions and tables for task initialization
pct.c – main application function that has init and event loop function
pct.h – header file for application module
pct_data.c – container for declaration of attributes, clusters, simple descriptor

The PCT application makes function calls to the following ZCL SE functions and ZDO API functions:

pct_LoadControlEventCB – this function is called when the PCT device received a load control command.

zclSE_LoadControl_Send_ReportEventStatus – When a load control command is received, the device sends a report event status command back to the ESP. Possible values for the event type for this particular sample app could be event received, event started, and event completed. The response structure (rsp) is made a global variable so that the process event loop can manipulate the eventStatus field once the PCT event is complete.

pct_HandleKeys – user switch events are processed here.

Once the PCT device joins the network, it goes through the state machine explained in Figure 43. *pct_KeyEstablish_ReturnLinkKey* is called to check if a link key has already been established with the ESP. If it hasn’t, it will set the osal event PCT_KEY_ESTABLISHMENT_REQUEST_EVT. The event handler for this in the process event loop will then call *zclGeneral_KeyEstablish_InitiateKeyEstablishment* to do the CBKE procedure. Upon its success, the application will receive a ZCL_KEY_ESTABLISH_IND system message. Nothing is done at this point, and the PCT device is ready to accept load control messages from the ESP.

When a load control command is received, the callback *pct_LoadControlEventCB* is executed. This callback function checks the issuer event id (0x12345678), the start time (0x00000000 = NOW) in order to make sure that it is not just blindly responding to a random load control event. Furthermore, it checks the *deviceGroupClass* to determine whether this load control event was for the PCT or load control device. The values within this load control command originate from the ESP. The correct string on the LCD is then displayed to indicate whether this is a load control device event or PCT event. It is assumed that the load control device belongs to the residential on/off load device class, and that the PCT belongs to the HVAC compressor/furnace device class. An OSAL timer event called PCT_LOAD_CTRL_EVT is then started to commence the load control event and flash the LED for the duration specified, which is 1 minute. When this timer event expires, the status response of event completed is sent back to the ESP, and the LED stops flashing. The user also sees a display on the LCD indicating that the PCT event is complete.

Note: The mechanics of the PCT and Load Control Device are the same. There are just slight differences in variable names and the type of message displayed on the LCD.

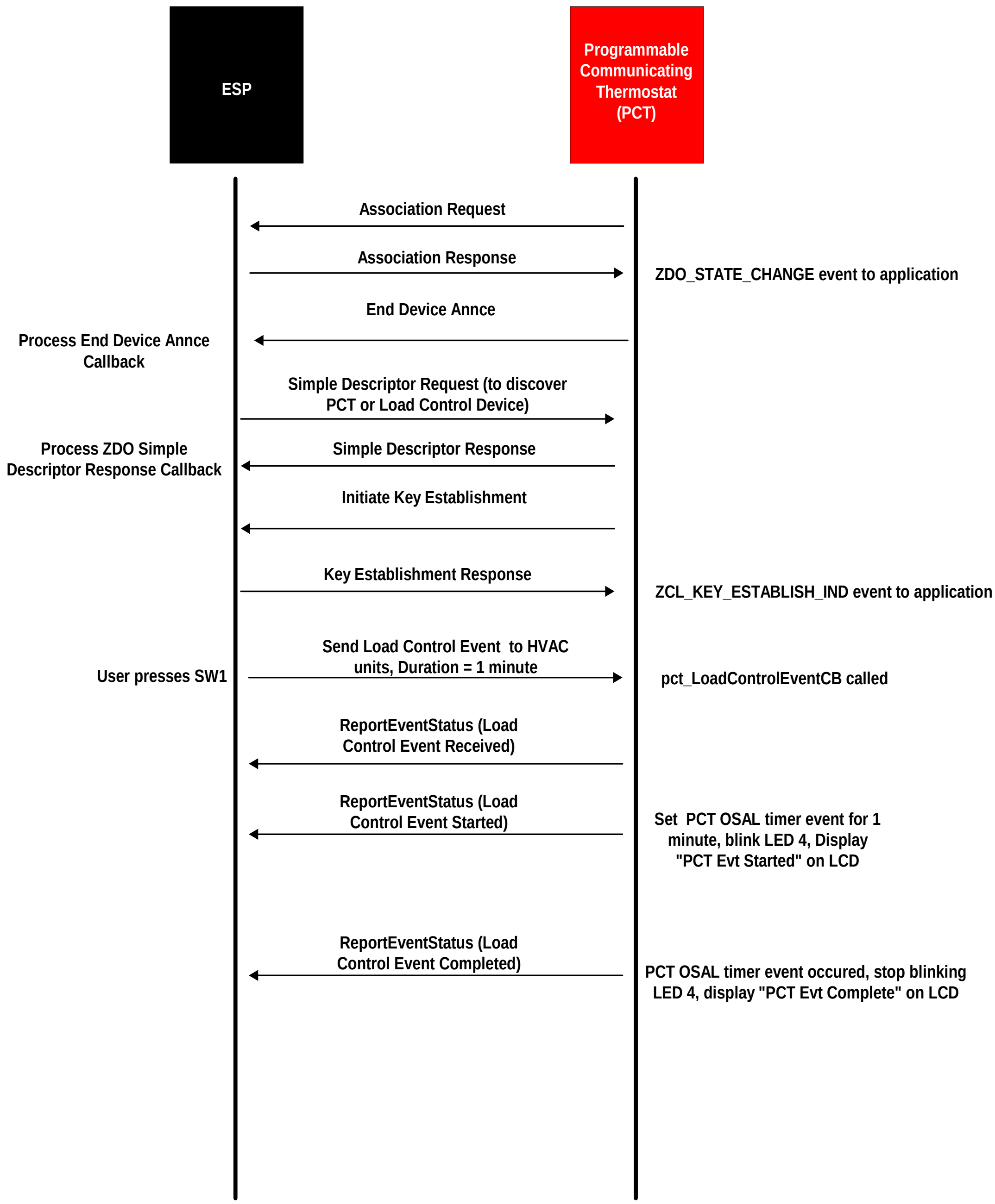


Figure 43: Sequence Diagram for a PCT

4.4.9. In Premise Display

The In Premise Display will use the *GetCurrentPrice* command to obtain the current pricing info from the ESP. The user can press SW2 to send an INTER-PAN version of the Get Current Price command to the ESP. The pricing information will be displayed on its LCD. The ESP will be able to use the SW3 button press to send a display MESSAGE command to the In Premise Display. This message will then be displayed on the LCD. See Figure 44 for a sequence diagram.

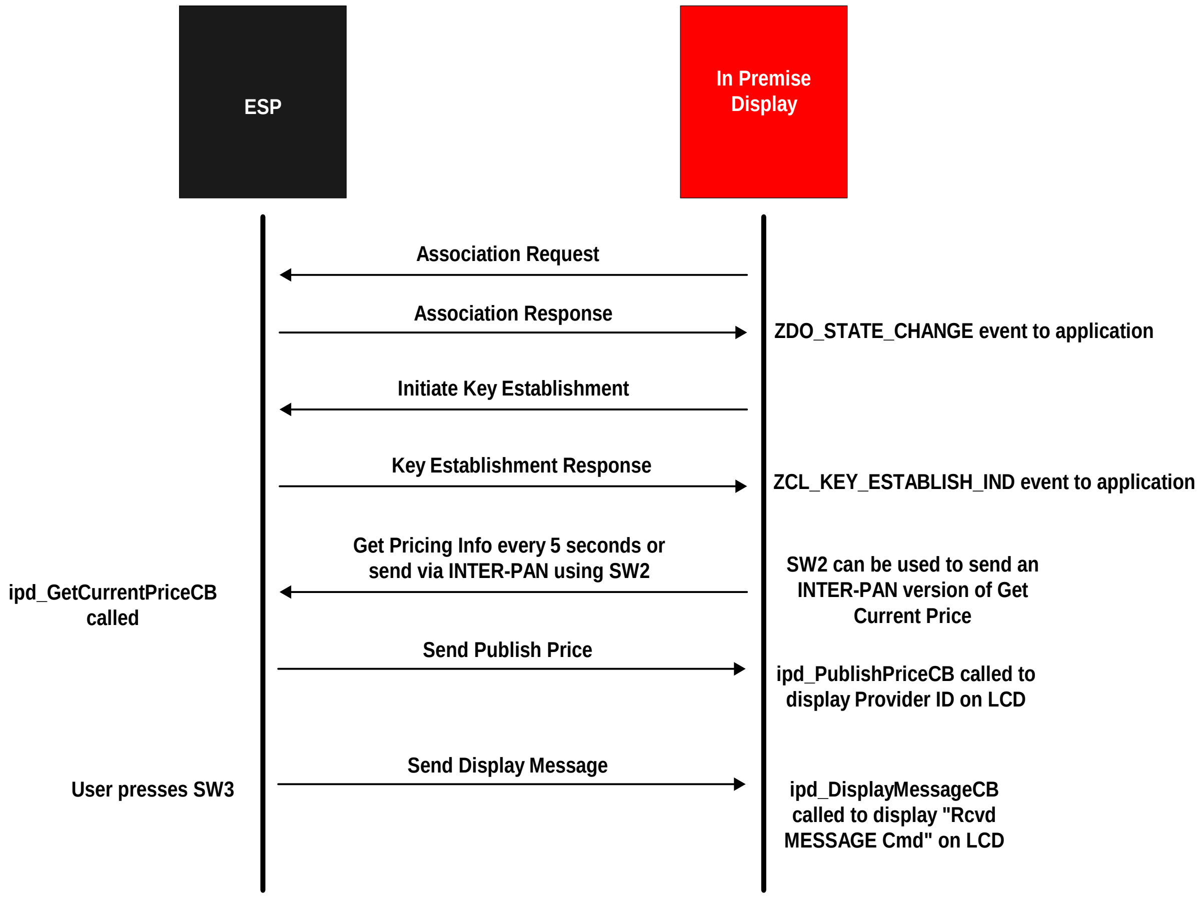


Figure 44: Sequence Diagram for an In Premise Display

The PCT application instance consists of the following modules:

OSAL_ipd.c – functions and tables for task initialization
ipd.c – main application function that has init and event loop function
ipd.h – header file for application module
ipd_data.c – container for declaration of attributes, clusters, simple descriptor

The IPD application makes function calls to the following ZCL SE functions and ZDO API functions:

zclSE_Pricing_Send_GetCurrentPrice – this function sends the get current price request to the ESP.

ipd_PublishPriceCB – this function is called when the IPD device receives the publish price command from the ESP, and displays the provider ID on the LCD.

ipd_HandleKeys – user switch events are processed here.

Once the IPD device joins the network, it goes through the state machine explained in Figure 44. *pct_KeyEstablish_ReturnLinkKey* is called to check if a link key has already been established with the ESP. If it hasn't, it will set the osal event IPD_KEY_ESTABLISHMENT_REQUEST_EVT. The event handler for this in the process event loop will then call *zclGeneral_KeyEstablish_InitiateKeyEstablishment* to do the CBKE procedure. Upon its success, the application will receive a ZCL_KEY_ESTABLISH_IND system message. An osal timer event called IPD_GET_PRICING_INFO_EVT is then started to send the get pricing info request every 5 seconds. The result of the pricing request is received via *ipd_PublishPriceCB* and is displayed on the LCD. Only the provider ID field of the published price payload is displayed.

4.4.10. Range Extender

The Range Extender device will not exchange application data with the ESP. It will be able to join the SE network, perform key establishment, and route packets. Figure 45 shows a sequence diagram for the Range Extender.

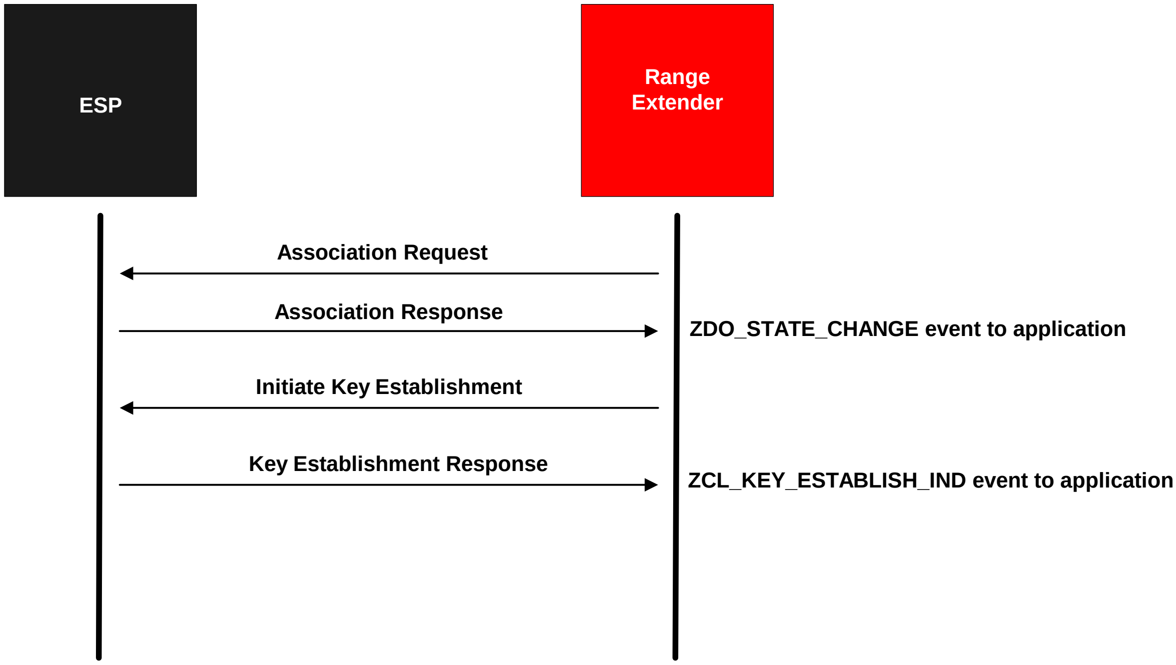


Figure 45: Sequence Diagram for a Range Extender

The Range Extender application instance consists of the following modules:

OSAL_rangeext.c - functions and tables for task initialization
rangeext.c – main application function that has init and event loop function
rangeext.h – header file for application module
rangeext_data.c – container for declaration of attributes, clusters, simple descriptor

The Range Extender application makes function calls to the following functions:

rangeext_HandleKeys – user switch events are processed here.

The Range Extender application does not send any application level SE messages, but it does join the network and perform key establishment. It functions as a standard ZigBee Pro router device.

4.4.11. Limitations of the SE Sample Application

This section explains the limitations of the SE sample application.

Trust Center Operation

- The trust center does not demonstrate how to refresh network keys.
- The trust center does not demonstrate how to manage an access control list
- The trust center assumes that joining devices have the same pre-configured trust center link key already established at compile time in the ZNP image or using the application to configure the corresponding NV item on the ZNP. It is assumed that the trust center link key is already available. Out of band means of deriving the trust center link key is out of the scope of this sample application.

Network Manager Operation

- The ESP is the only device that has the Network Manager functionality.
- The ZNP should be compiled with the NWK_MANAGER compile option in order to enable Network Manager functionality hooks.
- The ZNP default network manager application *ZDNwkMgr.c* is provided “as is” and there is no application level functionality incorporated to demonstrate this Network Manager application.

Secure Joining Operation

All devices must have the pre-configured Trust Center Link Key defined at compile time in the ZNP image, or configured via the application processor.

Key Establishment Operation

SE Key Establishment is always initiated by the joining device and its partner will always be the ESP.

Device Startup Behavior

The Smart Energy Profile spec mentions application best practices of controlling join/rejoin duty cycles. This sample app does not make any attempt at changing the join/rejoin mechanism as implemented in *ZDApp.c* in the ZNP image. The Smart Energy Profile spec says that end devices should not be more than 7.5 seconds. This sample application therefore supports a nominal poll rate of 8 seconds. The NWK_INDIRECT_MSG_TIMEOUT parameter in the f8wConfig.cfg file must be increased to a suggested value of 10 in order to buffer the message long enough to accommodate the 8 second poll period by the end device. The MAX_POLL_FAILURE_RETRIES parameter should also be set to 4 as during the CBKE procedure the ESP will be somewhat unresponsive to data requests during this time.

Load Control Device Behavior

There is no example of how to cancel a load control event from the ESP or how to supersede an ongoing load control event.

ESP Behavior

The ESP service discovery implementation is limited to supporting up to two load control devices at any given time, but could be easily modified to support more.

4.5. ZAP Proxy to ZNP SBL

As Chapter 3 described, the preferred method for updating the ZNP image is via the SBL embedded in the released ZNP images. If your H/W allows direct access to the ZNP USB or UART transport, existing PC Tools can be used to download a new ZNP image via SBL. Otherwise, for SPI transport or other transports that are not externally available, the ZAP will have to either control or proxy the SBL update. This section describes sample code that would be incorporated as an addition to any ZAP sample application and which implements an SBL update of the ZNP image by proxy to an existing PC Tool. Implementing the ZAP as the SBL master and accessing the ZNP image to install from ZAP-side internal or external non-volatile memory is a trivial (but completely H/W-dependent) enhancement to this ZAP-as-proxy sample application.

4.5.1. Hardware and Software setup

The sample code requires SPI transport to the ZNP and a UART connection to an external PC Tool. Such a setup is achieved with the MSP430F2618/5438 and CC2530EM described in 2.3.1 or 2.3.5.

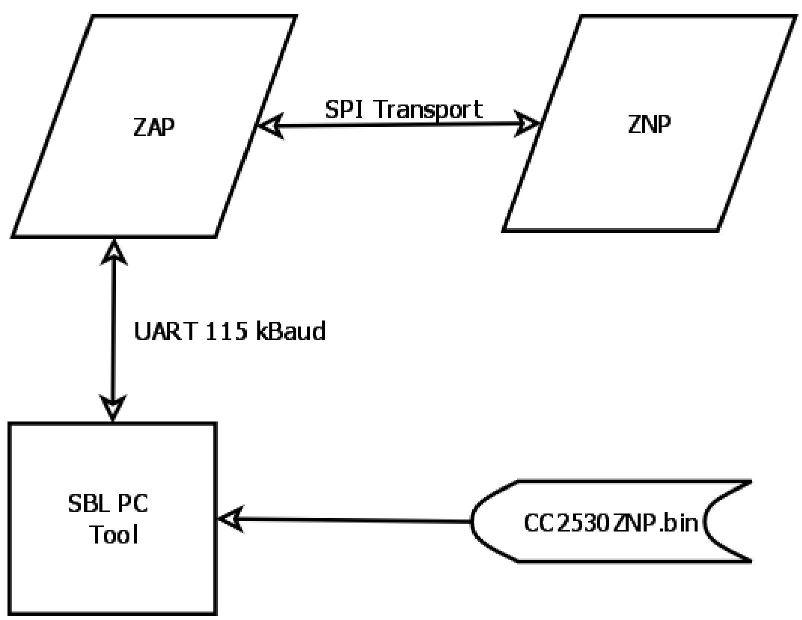


Figure 46: Flow diagram for ZAP Proxy to ZNP SBL

4.5.2. Required Settings

In the general settings in the ZAP configuration file, *zap.cfg* (see Section 4.1.2 for details,) the default setting of FALSE must be kept for both ***ZAP_ZNP_MT*** and ***ZAP_APP_MSG***:

```
#define TVSA_DLY_ANN              60000
// Pass through MT from ZAP serial port Rx from Z-Tool to ZNP…
```

```
-DZAP_ZNP_MT=FALSE
// The following functionality depends on ZAP_ZNP_MT
-DZAP_APP_MSG=FALSE
```

This is because the SBL proxy code will use the serial port and has not been designed to co-exist with the MT proxy (nor has the MT proxy code been designed to co-exist with something else.) This SBL proxy code must be enabled by changing the default setting from FALSE to TRUE for ***ZAP_SBL_PROXY***:

```
// The following functionality is mutually-exclusive with the set of
// ZAP_ZNP_MT & ZAP_APP_MSG
// (i.e. do not have both set to TRUE simultaneously.)
-DZAP_SBL_PROXY=TRUE
```

4.5.3. UART Connection

Cable the SmartRF05 serial port or EXP5438 USB-to-serial port cable to the PC and access the PC's corresponding COM port with the ***SBDemo.exe*** tool. The SBDemo.exe tool can be found in **`C:\Texas Instruments\ZAP-MSP430-x.x.x\Tools\SBL Tool.`**

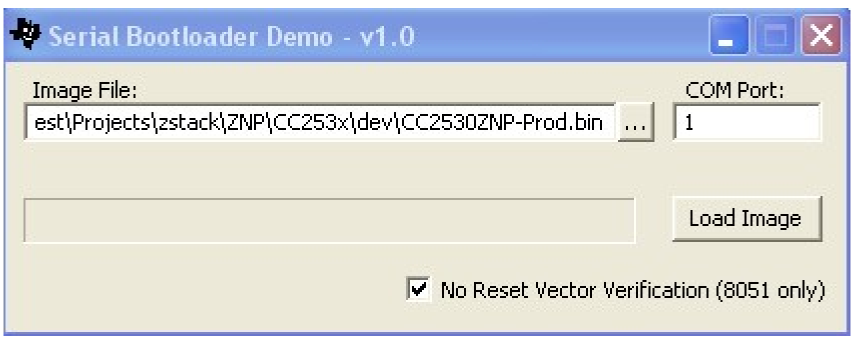


Figure 47: SBDemo PC Tool

To download the new ZNP image, point it to the .bin file of interest, select the correct COM port and check the box "No Reset Vector Verification (8051 only)". Then press the "Load Image" button to download the .bin file.

4.5.4. Incorporating the example

The TVSA Sample Application is used for demonstration purposes only – by merely changing the corresponding paths/names this proxy SBL code would easily be incorporated into any sample or proprietary ZAP application.

1. Find the sample code files here:
   `C:\Texas Instruments\ZAP-MSP430-x.x.x\Projects\zstack\ZAP\SBL\Source`

   And add these files to the target sample application as shown below:

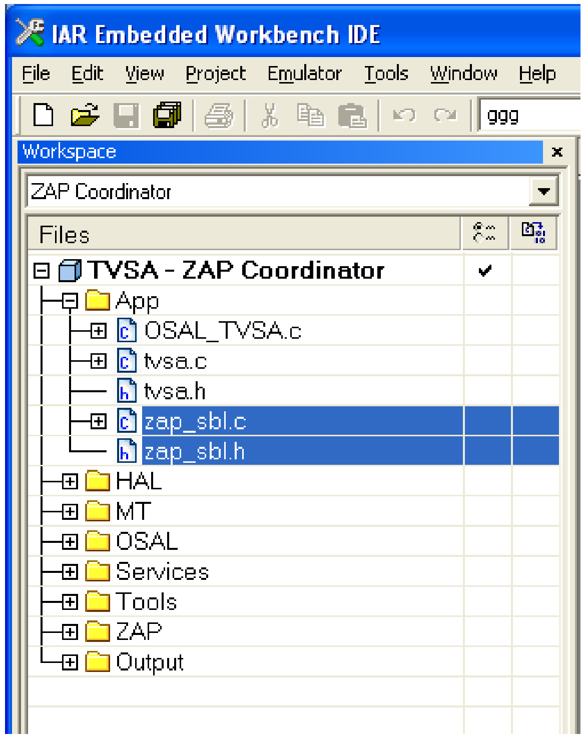
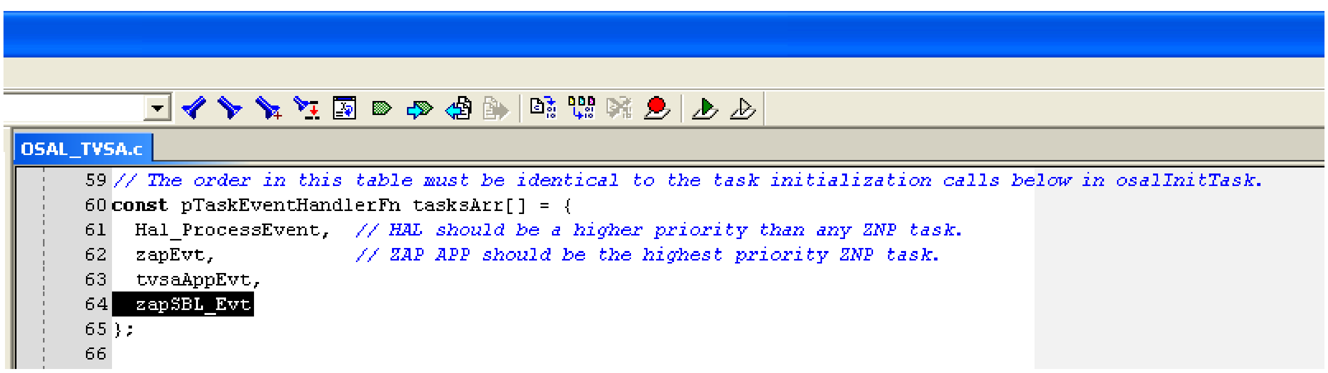


Figure 48: Adding the files for ZAP Proxy to ZNP SBL

2. Add the sample OSAL task to the target sample application as shown below:



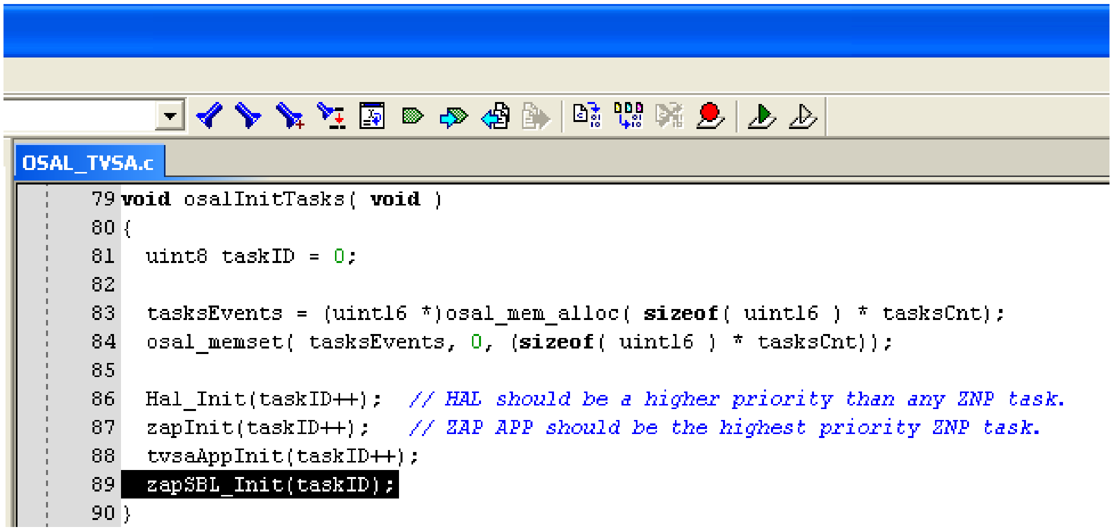


Figure 49: Adding the task for ZAP Proxy to ZNP SBL

Also add the following to the top of OSAL_TVSA.c:

```
extern void zapSBL_Init(uint8 id);
extern uint16 zapSBL_Evt(uint8 id, uint16 evts);
```

4.5.5. In Depth on the Example

In the following more details about the ZAP Proxy to ZNP SBL are given.

1. The zapSBL_Rx() function in zap_sbl.c, which is registered as the callback for the UART connected to the PC, will enter the SBL proxy mode by any Rx byte. This is done so early in parsing an incoming packet because the buffer for receiving it is not allocated so that the normal running environment is not penalized.

2. An OSAL timer is used to detect a loss of UART activity:
   ```
   osal_start_timerEx(zapSBL_TaskId, ZAP_SBL_EVT_EXIT, ZAP_SBL_DLY_EXIT)
   ```

3. The SBL proxy mode timeouts are defined in milliseconds at the top of the module:
   ```
   #define ZAP_SBL_DLY_EXIT  15000
   #define ZAP_SBL_DLY_WAIT  100
   ```

4. The SBL proxy mode is exited by a system reset:
   ```
   mask = ZAP_SBL_EVT_EXIT;
   HalReset();
   ```

FAQ

This Chapter addresses some frequently asked questions:

Q1: When do I need the IAR EW8051?

A1: You need the IAR EW8051 if you want to compile the Z-Stack code for the SoC; hence, you will for example need it when you want to build your own ZNP images (hex-files). The latter you would have to do if you cannot or do not want to use the available ready-built images.

Q2: Is it possible to use the Kick Start edition of the IAR EW430 to compile the ZAP Sample applications?

A2: No, you need a version that is not code size limited (due to the code size of the sample applications; i.e. you need either the evaluation edition or the full license version.

Q3: Where can I find more information about the OSAL and HAL?

A3: Both are described in the standard Z-Stack documentation (after installing the Z-Stack [6] it can be found in C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents) and one should start reading with the *Z-Stack Developer's Guide* [1]. Then one could continue looking at the *OSAL API.pdf*, *Z-Stack HAL Porting Guide.pdf*, and *HAL Driver API.pdf*

Q4: Can the application on the ZAP use APS fragmentation?

A4: Yes, fragmentation is supported.

Q5: Where is the trust center (TC), used for security, located?

A5: The trust center is implemented on the Coordinator ZNP image (if security is enabled).

Q6: Why are there several configuration files: *zap.cfg*, *znp.cfg* and *f8wConfig.cfg*?

A6: The sample application on the ZAP configures important parameters such as channel list, PAN id and thus, these should be changed in the *zap.cfg* file (see Section 4.1.2 for details). The settings in the *znp.cfg* and *f8wConfig.cfg*, like the default channel list and PAN id settings are not relevant as they will be reconfigured by the ZAP based on *zap.cfg*. The configuration files *znp.cfg* and *f8wConfig.cfg* are relevant for the user that does not want to use pre-built ZNP images, but instead wants to configure and built customized ZNP images (e.g. changing the security settings see described in Section 3.5 and Section 4.4.3 for details).

Q7: Isn't there a potential race condition where you have MRDY asserted the same time SRDY asserts (for example as AF data comes in asynchronously while you try to send a command to the ZNP)? Does the low level driver check for SRDY high before asserting MRDY?

A7: The ZNP is the slave and the ZAP is the master. The slave does whatever the master wants, regardless of which one pulled the "ready line" first – thus, by definition of the RPC protocol, there is no race or potential race.

There are two possible scenarios to consider:
1. Slave is ready with an AREQ, it asserts its SRDY.
2. Master is ready with an SREQ, it asserts its MRDY.

Whether the 2 lines asserted at the exact same moment in time or nanoseconds apart, the slave is bound by protocol to sit there holding its SRDY ready – it cannot de-assert its SRDY without being led through the protocol by the master. After the master asserts its MRDY, it is bound by protocol to sit there holding its MRDY ready until the slave asserts its SRDY. When finally the master is sure that it is asserting its MRDY and the slave is asserting its SRDY, the master proceeds with whatever it wants to do on the SPI according to protocol, which at this step are 2 options:

A. Make a "poll for data" which would allow the slave to regurgitate its AREQ. But we know the master won't be doing this, because it had an SREQ ready. So it will do B. in this scenario.
B. Make a SREQ according to protocol. And the slave, being a slave, is obliged to follow the steps of an SREQ even though it has in its queue one or more AREQ's ready to go.

---

5. References

[1] Z-Stack Developer's Guide - C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents\Z-Stack Developer's Guide.pdf

[2] CC2530-ZNP Interface Specification - C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents\CC2530ZNP_Interface_Specification.pdf

[3] IAR Embedded Workbench for 8051 (www.iar.com/ew8051; www.iar.com/ti_zigbee)

[4] IAR Embedded Workbench for MSP430 (www.iar.com/ew430; www.iar.com/ti_zigbee)

[5] Texas Instruments SmartRF Flash Programmer (http://focus.ti.com/docs/toolsw/folders/print/flash-programmer.html)

[6] Texas Instruments Z-Stack – www.ti.com/z-stack

[7] MSP430 based ZAP sample code - ZAP-MSP430-x.x.x.exe – www.ti.com/z-stack

[8] CC2530 Product folder – http://focus.ti.com/docs/prod/folders/print/cc2530.html

[9] CC2531 Product folder – http://focus.ti.com/docs/prod/folders/print/cc2531.html

[10] CC-Debugger – http://focus.ti.com/docs/toolsw/folders/print/cc-debugger.html

[11] CC2531USBDongle – http://focus.ti.com/docs/toolsw/folders/print/cc2531emk.html

[12] CC2520DK – http://focus.ti.com/docs/toolsw/folders/print/cc2520dk.html

[13] IAR EW8051 User Guide (EW8051_UserGuide.pdf) C:\Program Files\IAR Systems\EW8051_MCS-51_v7.51A\8051\doc\EW8051_UserGuide.pdf

[14] ZigBee Sensor Monitor (http://www.ti.com/litv/zip/swrc096d) & Z-Stack Sensor Monitor User's Guide (http://www.ti.com/litv/pdf/swru157d)

[15] MSP430 USB Debugging Interface – (http://focus.ti.com/docs/toolsw/folders/print/msp-fet430uif.html)

[16] CC2520DK User's Guide – (http://www.ti.com/litv/pdf/swru138)

[17] SmartRF05EB User's Guide - (http://www.ti.com/litv/pdf/swru210)

[18] MSP-EXP430F5438 Experimenter Board User's Guide – (http://www.ti.com/lit/pdf/slau263)

[19] Z-Stack Smart Energy Developer's Guide - C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents\ Z-Stack Smart Energy Developer's Guide.pdf

[20] Z-Stack Sample Applications Document - C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents\ Z-Stack Sample Applications.pdf

[21] Daintree Whitepaper "Understanding ZigBee Commissioning"; http://www.daintree.net/resources/whitepapers

[22] Ubiqua Protocol Analyzer from Ubilogix; www.ubilogix.com

[23] Z-Stack ZCL API Document - C:\Texas Instruments\ZStack-CC2530-x.x.x-x.x.x\Documents\ Z-Stack ZCL API.pdf

