Z-Stack Developer's Guide

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Texas Instruments, Inc.
San Diego, California USA

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1. Introduction

1.1 Purpose
This document explains some of the components of the Texas Instruments ZigBee stack and their functioning. It explains the configurable parameters in the ZigBee stack and how they may be changed by the application developer to suit the application requirements.

1.2 Scope
This document describes concepts and settings for the Texas Instruments Z-Stack™ Release. This is a ZigBee-2007 compliant stack for the ZigBee and ZigBee PRO stack profiles.

1.3 Acronyms

AF	Application Framework
AES	Advanced Encryption Standard
AIB	APS Information Base
API	Application Programming Interface
APS	Application Support Sub-Layer
APSDE	APS Date Entity
APSME	APS Management Entity
ASDU	APS Service Datagram Unit
BSP	Board Support Package – taken together, HAL & OSAL comprise a rudimentary operating system commonly referred to as a BSP
CCM*	Enhanced counter with CBC-MAC mode of operation
EPID	Extended PAN ID
HAL	Hardware (H/W) Abstraction Layer
MSG	Message
NHLE	Next Higher Layer Entity
NIB	Network Information Base
NWK	Network
OSAL	Operating System (OS) Abstraction Layer
OTA	Over-The-Air
PAN	Personal Area Network
SE	Smart Energy
ZDO	ZigBee Device Object

1.4 Reference Documents

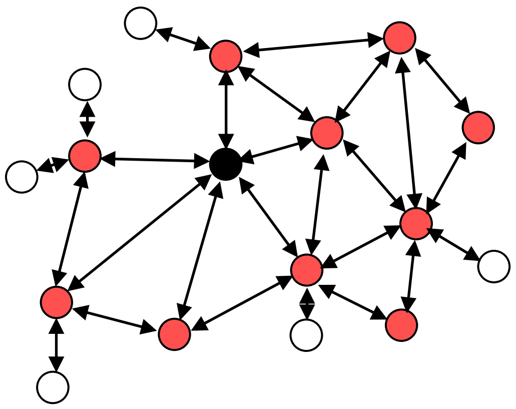
[1]	ZigBee Specification, R20, ZigBee Alliance document number 053474r20ZB.
[2]	Z-Stack API (SWRA195)
[3]	Z-Stack OSAL API (SWRA194)

2. ZigBee

A ZigBee network is a multi-hop network with battery-powered devices. This means that two devices that wish to exchange data in a ZigBee network may have to depend on other intermediate devices to be able to successfully do so. Because of this cooperative nature of the network, proper functioning requires that each device (i) perform specific networking functions and (ii) configure certain parameters to specific values. The set of networking functions that a device performs determines the role of the device in the network and is called a ***device type***. The set of parameters that need to be configured to specific values, along with those values, is called a ***stack profile***.

2.1 Device Types

There are three logical device types in a ZigBee network – (i) Coordinator (ii) Router and (iii) End-device. A ZigBee network consists of a Coordinator node and multiple Router and End-device nodes. Note that the device type does not in any way restrict the type of application that may run on the particular device.



An example network is shown in the diagram above, with the ZigBee Coordinator (black), the Routers (red), and the End Devices (white).

2.1.1 Coordinator

This is the device that "starts" a ZigBee network. It is the first device on the network. The coordinator node scans the RF environment for existing networks, chooses a channel and a network identifier (also called PAN ID) and then starts the network.

The coordinator node can also be used, optionally, to assist in setting up security and application-level bindings in the network.

Note that the role of the Coordinator is mainly related to starting up and configuring the network. Once that is accomplished, the Coordinator behaves like a Router node (or may even go away). The continued operation of the network does not depend on the presence of the Coordinator due to the distributed nature of the ZigBee network.

2.1.2 Router

A Router performs functions for (i) allowing other devices to join the network (ii) multi-hop routing (iii) assisting in communication for its child battery-powered end devices.

In general, Routers are expected to be active all the time and thus have to be mains-powered.

2.1.3 End-device

An end device has no specific responsibility for maintaining the network infrastructure, so it can sleep and wake up as it chooses. Thus it can be a battery-powered node.

Generally, the memory requirements (especially RAM requirements) are lower for an end device.

Notes:
In Z-Stack, the device type is usually determined at compile-time via compile options (`ZDO_COORDINATOR` and `RTR_NWK`). All sample applications are provided with separate project files to build each device type.

2.2 Stack Profile

The set of stack parameters that need to be configured to specific values, along with the above device type values, is called a ***stack profile***. The parameters that comprise the stack profile are defined by the ZigBee Alliance.

All devices in a network must conform to the same stack profile (i.e., all devices must have the stack profile parameters configured to the same values).

The ZigBee Alliance has defined two different stack profiles for the ZigBee-2007 specification, Zigbee and Zigbee PRO, with the goal of promoting interoperability. All devices that conform to this stack profile will be able to work in a network with devices from other vendors that also conform to it.

If application developers choose to change the settings for any of these parameters, they can do so with the caveat that those devices will no longer be able to interoperate with devices from other vendors that choose to follow the ZigBee specified stack profile. Thus, developers of "closed networks" may choose to change the settings of the stack profile variables. These stack profiles are called "network-specific" stack profile.

The stack profile identifier that a device conforms to is present in the beacon transmitted by that device. This enables a device to determine the stack profile of a network before joining to it. The "network-specific" stack profile has an ID of 0 while the ZigBee stack profile has ID of 1, and a ZigBee PRO stack profile has ID of 2. The stack profile is configured by the `STACK_PROFILE_ID` parameter in `nwk_globals.h` file.

Normally, a device of 1 profile (ex. ZigBee PRO) joins a network with the same profile. If a router of 1 profile (ex. ZigBee PRO) joins a network with a different profile (ex. ZigBee-2007), it will join as a non-sleeping end device. An end device of 1 profile (ex. ZigBee PRO) will always be an end device in a network with a different profile.

3. Addressing

3.1 Address types

ZigBee devices have two types of addresses. A 64-bit *IEEE address* (also called *MAC address* or *Extended address*) and a 16-bit *network address* (also called *logical address* or *short address*).

The 64-bit address is a globally unique address and is assigned to the device for its lifetime. It is usually set by the manufacturer or during installation. These addresses are maintained and allocated by the IEEE. More information on how to acquire a block of these addresses is available at http://standards.ieee.org/regauth/oui/index.shtml. The 16-bit address is assigned to a device when it joins a network and is intended for use while it is on the network. It is only unique within that network. It is used for identifying devices and sending data within the network.

3.2 Network address assignment

3.2.1 Tree Addressing

ZigBee 2007 uses a distributed addressing scheme for assigning the network addresses. This scheme ensures that all assigned network addresses are unique throughout the whole network. This is necessary so that there is no ambiguity about which device a particular packet should be routed to. Also, the distributed nature of the addressing algorithm ensures that a device only has to communicate with its parent device to receive a unique network-wide address. There is no need for network-wide communication for address assignment and this helps in scalability of the network.

The addressing scheme requires that some parameters are known ahead of time and are configured in each router that joins the network. These are the `MAX_DEPTH`, `MAX_ROUTERS` and `MAX_CHILDREN` parameters. These are part of the stack profile and the ZigBee-2007 stack profile has defined values for these parameters (`MAX_DEPTH` = 5, `MAX_CHILDREN` = 20, `MAX_ROUTERS` = 6).

The `MAX_DEPTH` determines the maximum depth of the network. The coordinator is at depth 0 and its child nodes are at depth 1 and their child nodes are at depth 2 and so on. Thus the `MAX_DEPTH` parameter limits how "long" the network can be physically.

The `MAX_CHILDREN` parameter determines the maximum number of child nodes that a router (or coordinator) node can possess.

The `MAX_ROUTERS` parameter determines the maximum number of router-capable child nodes that a router (or coordinator) node can possess. This parameter is a subset of the `MAX_CHILDREN` parameter and the remaining (`MAX_CHILDREN` – `MAX_ROUTERS`) entries are for end devices.

If developers wish to change these values, they need to follow the following steps:

- First it must be ensured that the new values for these parameters are legal. Since the total address space is limited to about 2^{16}, there are limits on how large these parameters can be set to.

- After choosing legal values, the developer needs to ensure not to use the standard stack profile and instead set it to network-specific (i.e. change the `STACK_PROFILE_ID` in `nwk_globals.h` to `NETWORK_SPECIFIC`) because the values are different from the values defined for the ZigBee profile. Then the `MAX_DEPTH` parameter in `nwk_globals.h` may be set to the appropriate value.

- In addition, the array's `CskipChldrn` and `CskipRtrs` must be set in the `nwk_globals.c` file. These arrays are populated with the values for `MAX_CHILDREN` and `MAX_ROUTERS` value for the first `MAX_DEPTH` indices followed by a zero value.

3.2.2 Stochastic Addressing

ZigBee PRO uses a stochastic (random) addressing scheme for assigning the network addresses. This addressing scheme randomly assigns short addresses to new devices, and then uses the rest of the devices in the network to ensure that there are no duplicate addresses. When a device joins, it receives its randomly generated address from its parent. The new network node then generates a "Device Announce" (which contains its new short address and its extended address) to the rest of the network. If there is another device with the same short address, a node (router) in the network will send out a broadcast "Network Status – Address Conflict" to the entire network and all devices with the conflicting short address will change its short address. When the conflicted devices change their address they issue their own "Device Announce" to check their new address for conflicts within the network.

End devices do not participate in the "Address Conflict". Their parents do that for them. If an "Address Conflict" occurs for an end device, its parent will issue the end device a "Rejoin Response" message to change the end device's short address and the end device issues a "Device Announce" to check their new address for conflicts within the network.

When a "Device Announce" is received, the association and binding tables are updated with the new short address, routing table information is not updated (new routes must be established). If a parent determines that the "Device Announce" pertains to one of its end device children, but it didn't come directly from the child, the parent will assume that the child moved to another parent.

3.3 Addressing in Z-Stack

In order to send data to a device on the ZigBee network, the application generally uses the `AF_DataRequest()` function. The destination device to which the packet is to be sent is of type `afAddrType_t` (defined in `ZComDef.h`).

```
typedef struct
{
  union
  {
    uint16      shortAddr;
    ZLongAddr_t extAddr;
  } addr;
  afAddrMode_t addrMode;
  byte endPoint;
} afAddrType_t;
```

Note that in addition to the network address, the address mode parameter also needs to be specified. The destination address mode can take one of the following values (AF address modes are defined in `AF.h`)

```
typedef enum
{
  afAddrNotPresent = AddrNotPresent,
  afAddr16Bit      = Addr16Bit,
  afAddr64Bit      = Addr64Bit,
  afAddrGroup      = AddrGroup,
  afAddrBroadcast  = AddrBroadcast
} afAddrMode_t;
```

The address mode parameter is necessary because, in ZigBee, packets can be unicast, multicast or broadcast. A unicast packet is sent to a single device, a multicast packet is destined to a group of devices and a broadcast packet is generally sent to all devices in the network. This is explained in more detail below.

3.3.1 Unicast

This is the normal addressing mode and is used to send a packet to a single device whose network address is known. The `addrMode` is set to `Addr16Bit` and the destination network address is carried in the packet.

3.3.2 Indirect

This is when the application is not aware of the final destination of the packet. The mode is set to `AddrNotPresent` and the destination address is not specified. Instead, the destination is looked up from a "binding table" that resides in the stack of the sending device. This feature is called Source binding (see later section for details on binding).

When the packet is sent down to the stack, the destination address and end point is looked up from the binding table and used. The packet is then treated as a regular unicast packet. If more than one destination device is found in the binding table, a copy of the packet is sent to each of them. If no binding entry is found, the packet will not be sent.

3.3.3 Broadcast

This address mode is used when the application wants to send a packet to all devices in the network. The address mode is set to `AddrBroadcast` and the destination address can be set to one of the following broadcast addresses:
`NWK_BROADCAST_SHORTADDR_DEVALL (0xFFFF)` – the message will be sent to all devices in the network (includes sleeping devices). For sleeping devices, the message is held at its parent until the sleeping device polls for it or the message is timed out (`NWK_INDIRECT_MSG_TIMEOUT` in `f8wConfig.cfg`).
`NWK_BROADCAST_SHORTADDR_DEVRXON` (`0xFFFD`) – the message will be sent to all devices that have the receiver on when idle (`RXONWHENIDLE`). That is, all devices except sleeping devices.
`NWK_BROADCAST_SHORTADDR_DEVZCZR` (`0xFFFC`) – the message is sent to all routers (including the coordinator).

3.3.4 Group Addressing

This address mode is used when the application wants to send a packet to a group of devices. The address mode is set to `afAddrGroup` and the `addr.shortAddr` is set to the group identifier.

Before using this feature, groups must be defined in the network, see `aps_AddGroup()` in the Z-Stack API [2] document.

Note that groups can also be used in conjunction with indirect addressing. The destination address found in the binding table can be either a unicast or a group address. Also note that broadcast addressing is simply a special case of group addressing where the groups are setup ahead of time.

Sample code for a device to add itself to a group with identifier 1:

```
aps_Group_t group;

// Assign yourself to group 1
group.ID = 0x0001;
group.name[0] = 6;  // First byte is string length
osal_memcpy( &(group.name[1]), "Group1", 6);
aps_AddGroup( SAMPLEAPP_ENDPOINT, &group );
```

3.4 Important Device Addresses

An application may want to know the address of its device and that of its parent. Use the following functions to get this device's address, defined in Z-Stack API [2] document:

- `NLME_GetShortAddr()` – returns this device's 16 bit network address.
- `NLME_GetExtAddr()` – returns this device's 64 bit extended address.
- Use the following functions to get this device's parent's addresses, defined in Z-Stack API [2] document. Note that the term "Coord" in these functions does not refer to the ZigBee Coordinator, but instead to the device's parent (MAC Coordinator):
- `NLME_GetCoordShortAddr()` – returns this device's parent's 16 bit short address.
- `NLME_GetCoordExtAddr()` – returns this device's parent's 64 bit extended address.

4. Binding

Binding is a mechanism to control the flow of messages from one application to another application (or multiple applications). The binding mechanism is implemented in all devices and is called source binding.

Binding allows an application to send a packet without knowing the destination address, the APS layer determines the destination address from its binding table, and then forwards the message on to the destination application (or multiple applications) or group.

4.1 Building a Binding Table

There are 3 ways to build a binding table:

- ZigBee Device Object Bind Request – a commissioning tool can tell the device to make a binding record.
- ZigBee Device Object End Device Bind Request – 2 devices can tell the coordinator that they would like to setup a binding table record. The coordinator will make the match up and create the binding table entries in the 2 devices.
- Device Application – An application on the device can build or manage a binding table.

4.1.1 ZigBee Device Object Bind Request

Any device or application can send a ZDO message to another device (over the air) to build a binding record for that other device in the network. This is called Assisted Binding and it will create a binding entry for the sending device.

4.1.1.1 The Commissioning Application

An application can do this by calling `ZDP_BindReq()` [defined in `ZDProfile.h`] with 2 applications (addresses and endpoints) and the cluster ID wanted in the binding record. The first parameter (target `dstAddr`) is the short address of the binding's source address (where the binding record will be stored). Calling `ZDP_UnbindReq()` can be used, with the same parameters, to remove the binding record.

The target device will send back a ZigBee Device Object Bind or Unbind Response message which the ZDO code on the coordinator will parse and notify `ZDApp.c` by calling `ZDApp_ProcessMsgCBs()` with the status of the action.

For the Bind Response, the status returned from the coordinator will be `ZDP_SUCCESS`, `ZDP_TABLE_FULL`, `ZDP_INVALID_EP`, or `ZDP_NOT_SUPPORTED`.

For the Unbind Response, the status returned from the coordinator will be `ZDP_SUCCESS`, `ZDP_NO_ENTRY`, `ZDP_INVALID_EP`, or `ZDP_NOT_SUPPORTED`.

4.1.1.2 ZigBee Device Object End Device Bind Request

This mechanism uses a button press or other similar action at the selected devices to bind within a specific timeout period. The End Device Bind Request messages are collected at the coordinator within the timeout period and a resulting Binding Table entry is created based on the agreement of profile ID and cluster ID. The default end device binding timeout (`APS_DEFAULT_MAXBINDING_TIME`) is 16 seconds (defined in `nwk_globals.h`), but can be changed if added to `f8wConfig.cfg` or as a compile flag.

For the Coordinator End Device Binding process, the coordinator registered `ZD_RegisterForZDOMsg()` to receive End Device Bind Request, Bind Response and Unbind Response ZDO messages in `ZDApp_RegisterCBs()` defined in `ZDApp.c`. When these message are received they are sent to `ZDApp_ProcessMsgCBs()`, where they are parsed and processed.

Coordinator end device binding is a toggle process. Meaning that the first time you go through the process, it will create a binding entry in the requesting devices. Then, when you go through the process again, it will remove the bindings in the requesting devices. That's why, in the following process, it will send an unbind, and wait to see if the unbind was successful. If the unbind was successful, the binding entry must have existed and been removed, otherwise it sends a binding request to make the entry.

When the coordinator receives 2 matching End Device Bind Requests, it will start the process of creating source binding entries in the requesting devices. The coordinator follows the following process, assuming matches were found in the ZDO End Device Bind Requests:

1. Send a ZDO Unbind Request to the first device. The End Device Bind is toggle process, so the unbind is sent first to remove an existing bind entry.
2. Wait for the ZDO Unbind Response, if the response status is `ZDP_NO_ENTRY`, send a ZDO Bind Request to make the binding entry in the source device. If the response status is `ZDP_SUCCESS`, move on to the cluster ID for the first device (the unbind removed the entry – toggle).
3. Wait for the ZDO Bind Response. When received, move on to the next cluster ID for the first device.
4. When the first device is done, do the same process with the second device.
5. When the second device is done, send the ZDO End Device Bind Response messages to both the first and second device.

4.1.2 Device Application Binding Manager

Another way to enter binding entries on the device is for the application to manage the binding table for itself. Meaning that the application will enter and remove binding table entries locally by calling the following binding table management functions, see Z-Stack API [2] Document – Binding Table Management section:

- `bindAddEntry()` – Add entry to binding table
- `bindRemoveEntry()` – Remove entry from binding table
- `bindRemoveClusterIdFromList()` – Remove a cluster ID from an existing binding table entry
- `bindAddClusterIdToList()` – Add a cluster ID to an existing binding table entry
- `bindRemoveDev()` – Remove all entries with an address reference
- `bindRemoveSrcDev()` – Remove all entries with a referenced source address
- `bindUpdateAddr ()` – Update entries to another address
- `bindFindExisting ()` – Find a binding table entry
- `bindIsClusterIDinList()` – Check for an existing cluster ID in a table entry
- `bindNumBoundTo()` – Number of entries with the same address (source or destination)
- `bindNumOfEntries()` – Number of table entries
- `bindCapacity()` – Maximum entries allowed
- `BindWriteNV()` – Update table in NV.

4.2 Configuring Source Binding

To enable source binding in your device include the `REFLECTOR` compile flag in `f8wConfig.cfg`. Also in `f8wConfig.cfg`, look at the 2 binding configuration items (`NWK_MAX_BINDING_ENTRIES` & `MAX_BINDING_CLUSTER_IDS`). `NWK_MAX_BINDING_ENTRIES` is the maximum number of entries in the binding table and `MAX_BINDING_CLUSTER_IDS` is the maximum number of cluster IDs in each binding entry.
The binding table is maintained in static RAM (not allocated), so the number of entries and the number of cluster IDs for each entry really affect the amount of RAM used. Each binding table entry is 6 bytes plus (`MAX_BINDING_CLUSTER_IDS * 2` bytes). Besides the amount of static RAM used by the binding table, the binding configuration items also affect the number of entries in the address manager.

5. Routing

5.1 Overview

A mesh network is described as a network in which the routing of messages is performed as a decentralized, cooperative process involving many peer devices routing on each others' behalf.

The routing is completely transparent to the application layer. The application simply sends data destined to any device down to the stack which is then responsible for finding a route. This way, the application is unaware of the fact that it is operating in a multi-hop network.

Routing also enables the "self healing" nature of ZigBee networks. If a particular wireless link is down, the routing functions will eventually find a new route that avoids that particular broken link. This greatly enhances the reliability of the wireless network and is one of the key features of ZigBee.

Many-to-one routing is a special routing scheme that handles the scenario where centralized traffic is involved. It is part of the ZigBee PRO feature set to help minimize traffic particularly when all the devices in the network are sending packets to a gateway or data concentrator. Many-to-one route discovery is described in details in Section 5.4.

5.2 Routing protocol

ZigBee uses a routing protocol that is based on the AODV (Ad-hoc On-demand Distance Vector) routing protocol for ad-hoc networks. Simplified for use in sensor networks, the ZigBee routing protocol facilitates an environment capable of supporting mobile nodes, link failures and packet losses.

Neighbor routers are routers that are within radio range of each other. Each router keeps track of their neighbors in a "neighbor table", and the "neighbor table" is updated when the router receives any message from a neighbor router (unicast, broadcast or beacon).

When a router receives a unicast packet, from its application or from another device, the NWK layer forwards it according to the following procedure. If the destination is one of the neighbors of the router (including its child devices) the packet will be transmitted directly to the destination device. Otherwise, the router will check its routing table for an entry corresponding to the routing destination of the packet. If there is an active routing table entry for the destination address, the packet will be relayed to the next hop address stored in the routing entry. If a single transmission attempt fails, the NWK layer will repeat the process of transmitting the packet and waiting for the acknowledgement, up to a maximum of `NWK_MAX_DATA_RETRIES` times. The maximum data retries in the NWK layer can be configured in `f8wconfig.cfg`. If an active entry cannot be found in the routing table or using an entry failed after the maximum number of retries, a route discovery is initiated and the packet is buffered until that process is completed.

ZigBee End Devices do not perform any routing functions. An end device wishing to send a packet to any device simply forwards it to its parent device which will perform the routing on its behalf. Similarly, when any device wishes to send a packet to an end device and initiate route discovery, the parent of the end device responds on its behalf.

Note that the ZigBee Tree Addressing (non-PRO) assignment scheme makes it possible to derive a route to any destination based on its address. In Z-Stack, this mechanism is used as an automatic fallback in case the regular routing procedure cannot be initiated (usually, due to lack of routing table space).

Also in Z-Stack, the routing implementation has optimized the routing table storage. In general, a routing table entry is needed for each destination device. But by combining all the entries for end devices of a particular parent with the entry for that parent device, storage is optimized without loss of any functionality.

ZigBee routers, including the coordinator, perform the following routing functions (i) route discovery and selection (ii) route maintenance (iii) route expiry.

5.2.1 Route Discovery and Selection

Route discovery is the procedure whereby network devices cooperate to find and establish routes through the network. A route discovery can be initiated by any router device and is always performed in regard to a particular destination device. The route discovery mechanism searches all possible routes between the source and destination devices and tries to select the best possible route.

Route selection is performed by choosing the route with the least possible cost. Each node constantly keeps track of "link costs" to all of its neighbors. The link cost is typically a function of the strength of the received signal. By adding up the link costs for all the links along a route, a “route cost” is derived for the whole route. The routing algorithm tries to choose the route with the least “route cost”.

Routes are discovered by using request/response packets. A source device requests a route for a destination address by broadcasting a Route Request (RREQ) packet to its neighbors. When a node receives an RREQ packet it in turn rebroadcasts the RREQ packet. But before doing that, it updates the cost field in the RREQ packet by adding the link cost for the latest link and makes an entry in its Route Discovery Table (5.3.2). This way, the RREQ packet carries the sum of the link costs along all the links that it traverses. This process repeats until the RREQ reaches the destination device. Many copies of the RREQ will reach the destination device traveling via different possible routes. Each of these RREQ packets will contain the total route cost along the route that it traveled. The destination device selects the best RREQ packet and sends back a Route Reply (RREP) back to the source.

The RREP is unicast along the reverse routes of the intermediate nodes until it reaches the original requesting node. As the RREP packet travels back to the source, the intermediate nodes update their routing tables to indicate the route to the destination. The Route Discovery Table, at each intermediate node, is used to determine the next hop of the RREP traveling back to the source of the RREQ and to make the entry in to the Routing Table.

Once a route is created, data packets can be sent. When a node loses connectivity to its next hop (it doesn’t receive a MAC ACK when sending data packets), the node invalidates its route by sending an RERR to all nodes that potentially received its RREP and marks the link as bad in its Neighbor Table. Upon receiving a RREQ, RREP or RERR, the nodes update their routing tables.

5.2.2 Route maintenance

Mesh networks provide route maintenance and self healing. Intermediate nodes keep track of transmission failures along a link. If a link (between neighbors) is determined as bad, the upstream node will initiate route repair for all routes that use that link. This is done by initiating a rediscovery of the route the next time a data packet arrives for that route. If the route rediscovery cannot be initiated, or it fails for some reason, a route error (RERR) packet is sent back to source of the data packet, which is then responsible for initiating the new route discovery. Either way the route gets re-established automatically.

5.2.3 Route expiry

The routing table maintains entries for established routes. If no data packets are sent along a route for a period of time, the route will be marked as expired. Expired routes are not deleted until space is needed. Thus routes are not deleted until it is absolutely necessary. The automatic route expiry time can be configured in `f8wconfig.cfg`. Set `ROUTE_EXPIRY_TIME` to expiry time in seconds. Set to 0 in order to turn off route expiry feature.

5.3 Table storage

The routing functions require the routers to maintain some tables.

5.3.1 Routing table

Each ZigBee router, including the ZigBee coordinator, contains a routing table in which the device stores information required to participate in the routing of packets. Each routing table entry contains the destination address, the next hop node, and the link status. All packets sent to the destination address are routed through the next hop node. Also entries in the routing table can expire in order to reclaim table space from entries that are no longer in use.

Routing table capacity indicates that a device routing table has a free routing table entry or it already has a routing table entry corresponding to the destination address. The routing table size is configured in `f8wconfig.cfg`. Set `MAX_RTG_ENTRIES` to the number of entries in the (default is 40). See the section on Route Maintenance for route expiration details.

5.3.2 Route discovery table

Router devices involved in route discovery, maintain a route discovery table. This table is used to store temporary information while a route discovery is in progress. These entries only last for the duration of the route discovery operation. Once an entry expires it can be used for another route discovery operation. Thus this value determines the maximum number of route discoveries that can be simultaneously performed in the network. This value is configured by setting the `MAX_RREQ_ENTRIES` in `f8wconfig.cfg`.

5.4 Many-to-One Routing Protocol

The following explains many-to-one and source routing procedure for users' better understanding of ZigBee routing protocol. In reality, all routings are taken care in the network layer and transparent to the application. Issuing many-to-one route discovery and route maintenance are application decisions.

5.4.1 Many-to-One Routing Overview

Many-to-one routing is adopted in ZigBee PRO to help minimize traffic particularly when centralized nodes are involved. It is common for low power wireless networks to have a device acting as a gateway or data concentrator. All nodes in the networks shall maintain at least one valid route to the central node. To achieve this, all nodes have to initiate route discovery for the concentrator, relying on the existing ZigBee AODV based routing solution. The route request broadcasts will add up and produce huge network traffic overhead. To better optimize the routing solution, many-to-one routing is adopted to allow a data concentrator to establish routes from all nodes in the network with one single route discovery and minimize the route discovery broadcast storm.

Source routing is part of the many-to-one routing that provides an efficient way for concentrator to send response or acknowledgement back to the destination. The concentrator places the complete route information from the concentrator to the destination into the data frame which needs to be transmitted. It minimizes the routing table size and route discovery traffic in the network.

5.4.2 Many-to-One Route Discovery

The following figure shows an example of the many-to-one route discovery procedure. To initiate many-to-one route discovery, the concentrator broadcast a many-to-one route request to the entire network. Upon receipt of the route request, every device adds a route table entry for the concentrator and stores the one hop neighbor that relays the request as the next hop address. No route reply will be generated.

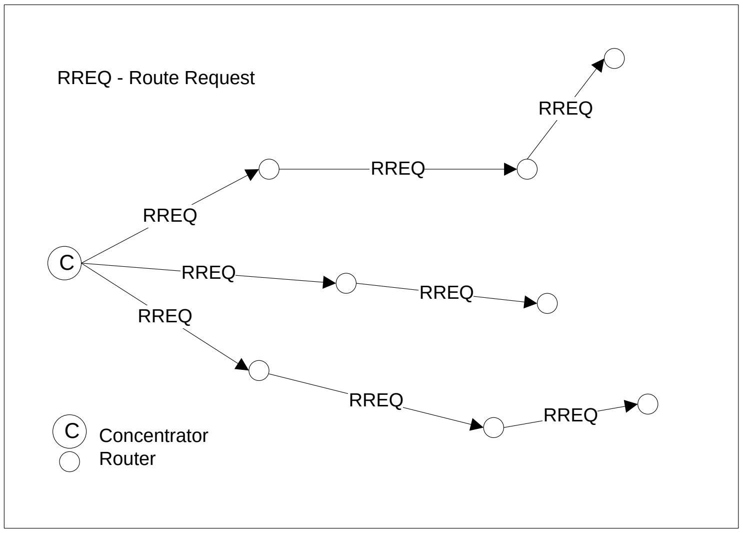


Figure 1: Many-to-one route discovery illustration

Many-to-one route request command is similar to unicast route request command with same command ID and payload frame format. The option field in route request is many-to-one and the destination address is 0xFFFC. The following Z-Stack API can be used for the concentrator to send out many-to-one route request. Please refer to the Z-Stack API [2] documentation for detailed usage about this API.

```
  ZStatus_t NLME_RouteDiscoveryRequest( uint16 DstAddress,
                                        byte options, uint8 radius )
```

The option field is a bitmask to specify options for the route request. It can have the following values:

Value	Description
0x00	Unicast route discovery
0x01	Many-to-one route discovery with route cache (the concentrator does not have memory constraints).
0x03	Many-to-one route discovery with no route cache (the concentrator has memory constraints)

When the option field has value 0x01 or 0x03, the `DstAddress` field will be overwritten with the many-to-one destination address 0xFFFC. Therefore, user can pass any value to `DstAddress` in the case of many-to-one route request.

5.4.3 Route Record Command

The above many-to-one route discovery procedure establishes routes from all devices to the concentrator. The reverse routing (from concentrator to other devices) is done by route record command (source routing scheme). The procedure of source routing is illustrated in Figure 2. R1 sends data packet DATA to the concentrator using the previously established many-to-one route and expects an acknowledgement back. To provide a route for the concentrator to send the ACK back, R1 sends route record command along with the data packet which records the routing path the data packet goes through and offers the concentrator a reverse path to send the ACK back.

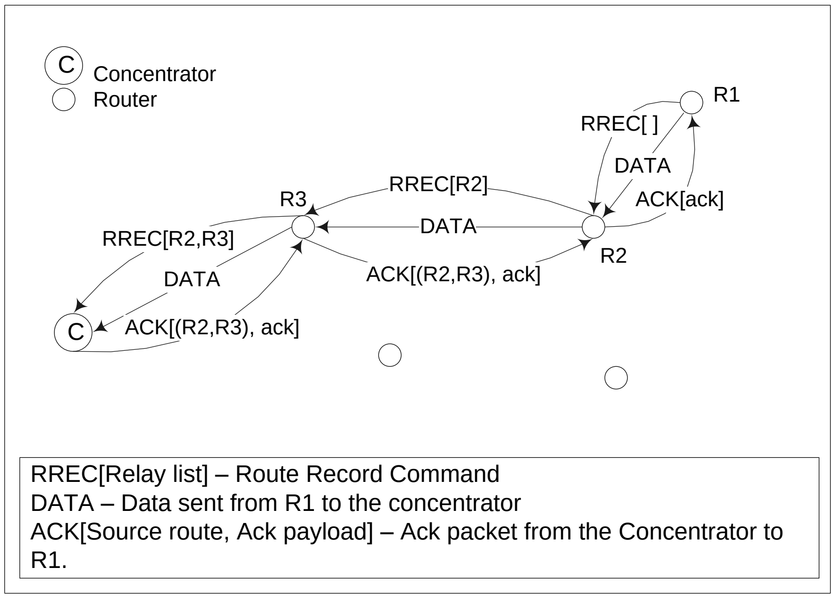

C Concentrator
Router
R1
RREC[ ]
DATA
ACK[ack]
R3
RREC[R2]
DATA
R2
RREC[R2,R3]
DATA
ACK[(R2,R3), ack]
C
ACK[(R2,R3), ack]
RREC[Relay list] – Route Record Command
DATA – Data sent from R1 to the concentrator
ACK[Source route, Ack payload] – Ack packet from the Concentrator to R1.

Figure 2: Route record command (source routing) illustration

Upon receipt of the route record command, devices on the relay path will append their own network addresses to the relay list in the route record command payload. By the time the route record command reaches the concentrator, it includes the complete routing path through which the data packet is relayed to the concentrator. When the concentrator sends ACK back to R1, it shall include the source route (relay list) in the network layer header of the packet. All devices receiving the packet shall relay the packet to the next hop device according to the source route. For concentrator with no memory constraints, it can store all route record entries it receives and use them to send packets to the source devices in the future. Therefore, devices only need to send route record command once. However, for concentrator without source route caching capability, devices always need to send route record commands along with data packets. The concentrator will store the source route temporarily in the memory and then discard it after usage.

In brief, many-to-one routing is an efficient enhancement to the regular ZigBee unicast routing when most devices in the network are funneling traffic to a single device. As part of the many-to-one routing, source routing is only utilized under certain circumstances. First, it is used when the concentrator is responding to a request initiated by the source device. Second, the concentrator should store the source route information for all devices if it has sufficient memory. If not, whenever devices issue request to the concentrator, they should also send route record along with it.

5.4.4 Many-to-One Route Maintenance

If a link failure is encountered while a device is forwarding a many-to-one routed frame (notice that a many-to-one routed frame itself has no difference from a regular unicast data packet, however, the routing table entry has a field to specify that the destination is a concentrator), the device will generate a network status command with code "Many-to-one route failure". The network status command will be relayed to the concentrator through a random neighbor and hopefully that neighbor still has a valid route to the concentrator. When the concentrator receives the route failure, the application will decide whether or not to re-issue a many-to-one route request.

When the concentrator receives network status command indicating many-to-one route failure, it passes the indication to the ZDO layer and the following ZDO callback function in `ZDApp.c` is called:

```
void ZDO_ManytoOneFailureIndicationCB()
```

By default, this function will redo a many-to-one route discovery to recover the routes. You can modify this function if you want a more complicated process other than the default.

5.5 Routing Settings Quick Reference

Setting Routing Table Size	Set `MAX_RTG_ENTRIES` Note: the value must be greater than 4. (See `f8wConfig.cfg`)
Setting Route Expiry Time	Set `ROUTE_EXPIRY_TIME` to expiry time in seconds. Set to 0 in order to turn off route expiry. (See `f8wConfig.cfg`)
Setting Route Discovery Table Size	Set `MAX_RREQ_ENTRIES` to the maximum number of simultaneous route discoveries enabled in the network. (See `f8wConfig.cfg`)
Enable Concentrator	Set `CONCENTRATOR_ENABLE` (See `ZGlobals.h`)
Setting Concentrator Property – With Route Cache	Set `CONCENTRATOR_ROUTE_CACHE` (See `ZGlobals.h`)
Setting Source Routing Table Size	Set `MAX_RTG_SRC_ENTRIES` (See `ZGlobals.h`)
Setting Default Concentrator Broadcast Radius	Set `CONCENTRATOR_RADIUS` (See `ZGlobals.h`)

5.6 Router Off-Network Association Cleanup

In case a ZigBee Router gets off network for a long period of time, its children will try to join an alternative parent. When the router is back online, the children will still appear in its child table, preventing proper routing of egress traffic to them.

In order to avoid this, it is recommended that routers prone to get off and on the network will have `zgRouterOffAssocCleanup` flag set to `TRUE` (mapped to NV item: `ZCD_NV_ROUTER_OFF_ASSOC_CLEANUP`):

```
uint8 cleanupChildTable = TRUE;
zgSetItem( ZCD_NV_ROUTER_OFF_ASSOC_CLEANUP, sizeof(cleanupChildTable),
           &cleanupChildTable );
```

When enabled, deprecated end device entries will be removed from the child table if traffic received from them was routed by another parent.

6. ZDO Message Requests

The ZDO module provides functions to send ZDO service discovery request messages and receive ZDO service discovery response messages. The following flow diagram illustrates the function calls need to issue an IEEE Address Request and receive the IEEE Address Response for an application.

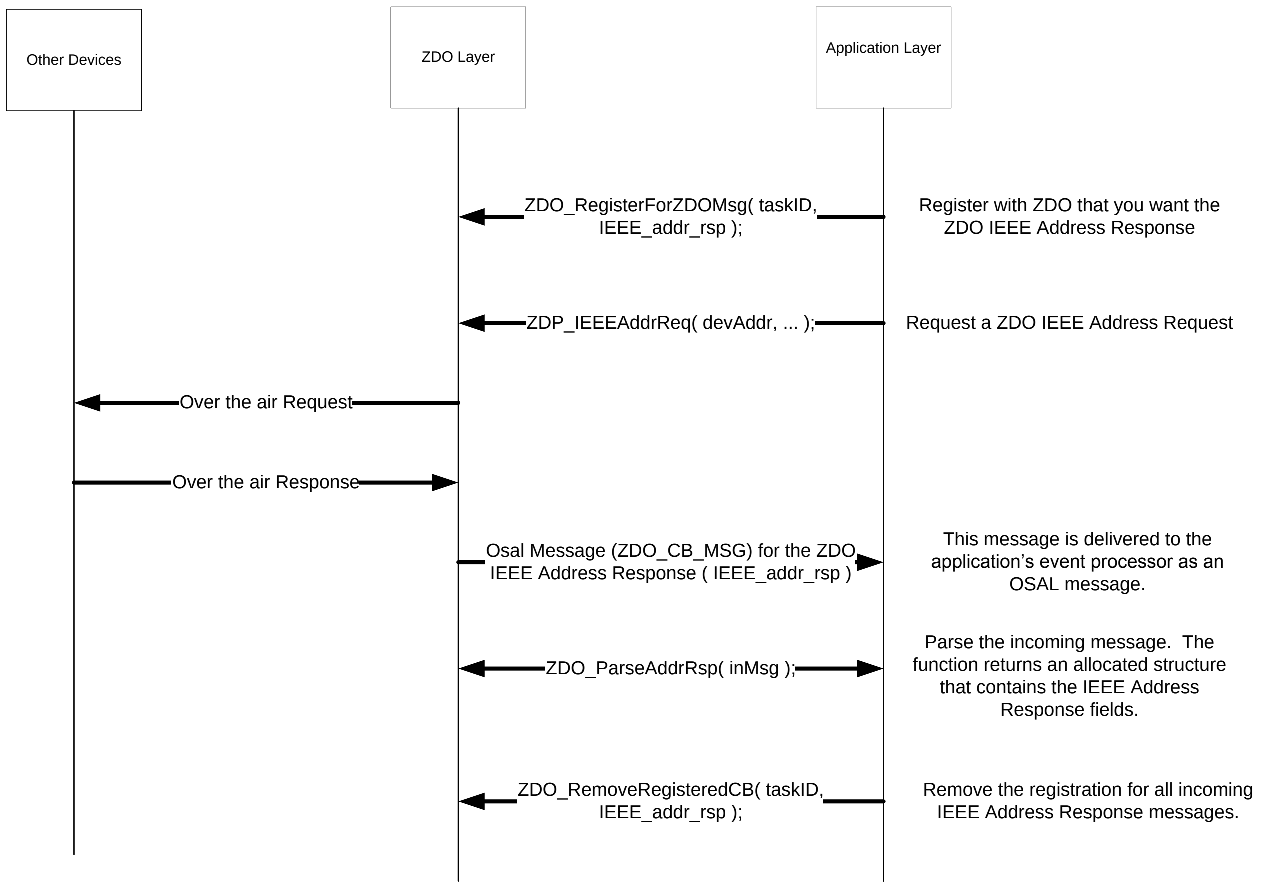

Other Devices
ZDO Layer
Application Layer
ZDO_RegisterForZDOMsg(taskID, IEEE_addr_rsp);
Register with ZDO that you want the ZDO IEEE Address Response
ZDP_IEEEAddrReq(devAddr, ...);
Request a ZDO IEEE Address Request
Over the air Request
Over the air Response
Osal Message (ZDO_CB_MSG) for the ZDO IEEE Address Response (IEEE_addr_rsp)
This message is delivered to the application's event processor as an OSAL message.
ZDO_ParseAddrRsp(inMsg);
Parse the incoming message. The function returns an allocated structure that contains the IEEE Address Response fields.
ZDO_RemoveRegisteredCB(taskID, IEEE_addr_rsp);
Remove the registration for all incoming IEEE Address Response messages.

Figure 3: ZDO IEEE Address Request and Response

In the following example, an application would like to know when any new devices join the network. The application would like to receive all ZDO Device Announce (Device_annce) messages.

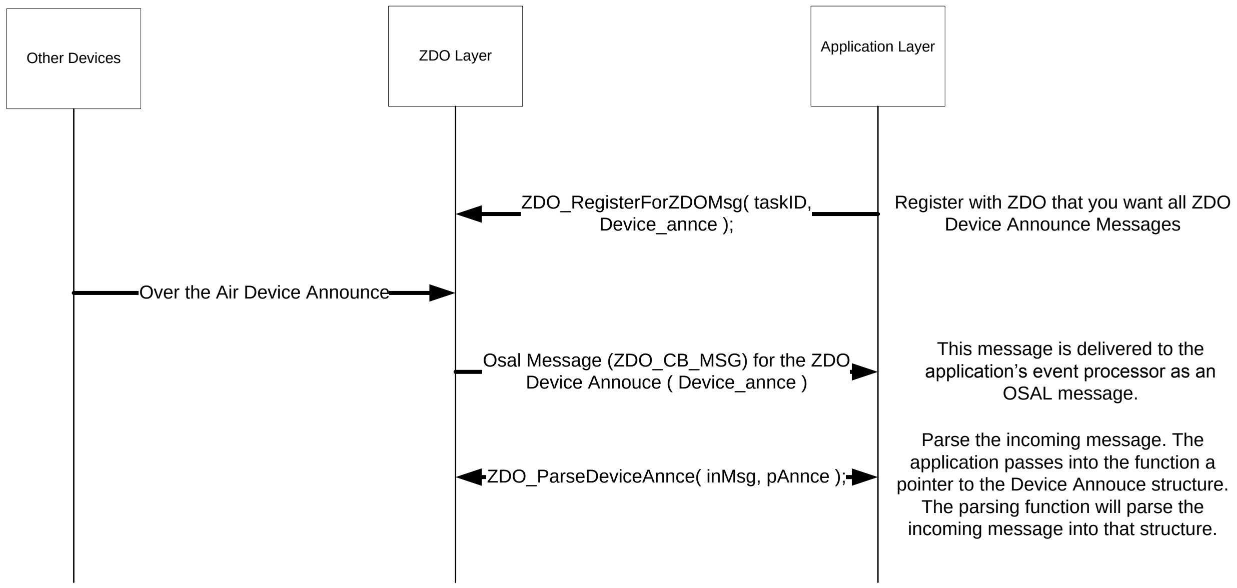

Other Devices
ZDO Layer
Application Layer
ZDO_RegisterForZDOMsg(taskID, Device_annce);
Register with ZDO that you want all ZDO Device Announce Messages
Over the Air Device Announce
Osal Message (ZDO_CB_MSG) for the ZDO Device Annouce (Device_annce)
This message is delivered to the application's event processor as an OSAL message.
ZDO_ParseDeviceAnnce(inMsg, pAnnce);
Parse the incoming message. The application passes into the function a pointer to the Device Annouce structure. The parsing function will parse the incoming message into that structure.

Figure 4: ZDO Device Announce delivered to an application

7. Portable Devices

End devices are automatically portable. Meaning that when an end device detects that its parent isn't responding (out of range or incapacitated) it will try to rejoin the network (joining a new parent). There are no setup or compile flags to setup this option.

The end device detects that a parent isn't responding either through polling (MAC data requests) failures and/or through data message failures. The sensitivity to the failures (amount of consecutive errors) is controlled by `MAX_POLL_FAILURE_RETRIES`, which is configurable in `f8wConfig.cfg` (the higher the number – the less sensitive and the longer it will take to rejoin).

When the network layer detects that its parent isn't responding, it will call `ZDO_SyncIndicationCB()`, which will initiate a "rejoin". The rejoin process will first orphan-scan for an existing parent, then scan for a potential parent and rejoin (network rejoin command) the network with the potential parent.

In a secure network, it is assumed that the device already has a key and a new key isn't issued to the device.

In a ZigBee PRO network, the end device's short address is retained when it moves from parent to parent. In a ZigBee network, because of the tree addressing, the new parent will give the end device a new address. In either case, routes to the moved end device have to be re-established either automatically (as the old one fails) or intentionally (by the application).

8. End-to-end acknowledgements

For non-broadcast messages, there are basically 2 types of message retry: end-to-end acknowledgement (APS ACK) and single-hop acknowledgement (MAC ACK). MAC ACKs are always on by default and are usually sufficient to guarantee a high degree of reliability in the network. To provide additional reliability, as well as to enable the sending device get confirmation that a packet has been delivered to its destination, APS acknowledgements may be used.

APS acknowledgement is done at the APS layer and is an acknowledgement system from the destination device to the source device. The sending device will hold the message until the destination device sends an APS ACK message indicating that it received the message. This feature can be enabled/disabled for each message sent with the `options` field of the call to `AF_DataRequest()`. The options field is a bit map of options, so OR in `AF_ACK_REQUEST` to enable APS ACK for the message that you are sending. The number of times that the message is retried (if APS ACK message isn't received) and the timeout between retries are configuration items in `f8wConfig.cfg`. `APSC_MAX_FRAME_RETRIES` is the number of retries the APS layer will send the message if it doesn't receive an APS ACK before giving up. `APSC_ACK_WAIT_DURATION_POLLED` is the time between retries.

9. Miscellaneous

9.1 Configuring channel

Every device must have a DEFAULT_CHANLIST (in f8wConfig.cfg) that controls the channel selection. For a ZigBee Coordinator, this list will be used to scan for a channel with the least amount of noise. For ZigBee Routers and End Devices, this list will be used to scan for existing networks to join.

9.2 Configuring the PAN ID and network to join

This is an optional configuration item to control which network a ZigBee Router or End Device will join. The ZDO_CONFIG_PAN_ID parameter in f8wConfig.cfg can be set to a value (between 0 and 0xFFFE). A coordinator will use this value as the PAN ID of the network that it starts. A router or end device will only join a network that has a PAN ID configured in this parameter. To turn this feature off, set the parameter to a value of 0xFFFF.

For further control of the joining procedure, the ZDO_NetworkDiscoveryConfirmCB function in the ZDApp.c should be modified. ZDO_NetworkDiscoveryConfirmCB() is called when the network layer has finished with the Network Discovery process, started by calling NLME_NetworkDiscoveryRequest() defined in the Z-Stack API [2] document.

9.3 Maximum payload size

The maximum payload size for an application is based on several factors. The MAC layer provides a constant payload length of 116 (can be changed in f8wConfig.cfg – MAC_MAX_FRAME_SIZE). The NWK layer requires a fixed header size, one size with security and one without security. The APS layer has a required, but variable, header size based on a variety of settings, including the ZigBee Protocol Version, APS frame control settings, etc. Ultimately, the user does not have to calculate the maximum payload size using the aforementioned factors. The AF module provides an API that allows the user to query the stack for the maximum payload size, or the maximum transport unit (MTU). The user can call the function, afDataReqMTU() (see AF.h) which will return the MTU, or maximum payload size.

```
typedef struct
{
  uint8              kvp;
  APSDE_DataReqMTU_t aps;
} afDataReqMTU_t;

uint8 afDataReqMTU( afDataReqMTU_t* fields )
```

Currently the only field that should be set in the afDataReqMTU_t structure is kvp, which indicates whether KVP is being used and this field should be set to FALSE. The aps field is reserved for future use.

9.4 Leave Network

The ZDO Management implements the function, ZDO_ProcessMgmtLeaveReq(), which offers access to the "NLME-LEAVE.request" primitive. The "NLME-LEAVE.request" allows a device to remove itself or remove a child device. The ZDO_ProcessMgmtLeaveReq() removes the device based on the provided IEEE address. If a device removes itself, it will wait for approximately 5 seconds and then reset. Once the device resets, it will come back up in an idle state. It will not attempt to associate or rejoin. If a device removes a child device it will remove the device from the local "association table". The NWK address will only be reused in the case where a child device is a ZigBee End Device. In the case of a child ZigBee Router, the NWK address will not be reused.
If the parent of a child device leaves the network, the child will stay on the network.

In version R20 of the ZigBee PRO specification [1], processing of "NWK Leave Request" is configurable for Routers. The application controls this feature by setting the zgNwkLeaveRequestAllowed variable to TRUE (default value) or FALSE, to allow/disallow a Router to leave the network when a "NWK Leave Request" is received. `zgNwkLeaveRequestAllowed` is defined and initialized in `ZGlobals.c`, and the corresponding NV item, `ZCD_NV_NWK_LEAVE_REQ_ALLOWED`, is defined in `ZComDef.h`.

9.5 Descriptors

All devices in a ZigBee network have descriptors that describe the type of device and its applications. This information is available to be discovered by other devices in the network.

Configuration items are setup and defined in `ZDConfig.c` and `ZDConfig.h`. These 2 files also contain the Node, Power Descriptors and default User Descriptor. Make sure to change these descriptors to define your device.

9.6 Non-Volatile Memory Items

9.6.1 Global Configuration Non-Volatile Memory

Global device configuration items are stored in `ZGlobal.c`, things like PAN ID, key information, network settings. The default values for most of these items are stored in `f8wConfig.cfg`. These items are stored in RAM and accessed throughout Z-Stack. To initialize the non-volatile memory area to store these items, include the NV_INIT compile flag in your project.

9.6.2 Network Layer Non-Volatile Memory

A ZigBee device has lots of state information that needs to be stored in non-volatile memory so that it can be recovered in case of an accidental reset or power loss. Otherwise, it will not be able to rejoin the network or function effectively.

To enable this feature include the `NV_RESTORE` compile option. Note that this feature must usually be always enabled in a real ZigBee network. The ability to turn it off is only intended to be used in the development stage.
The ZDO layer is responsible for the saving and restoring of the Network Layer’s vital information. This includes the Network Information Base (NIB - Attributes required to manage the network layer of the device); the list of child and parent devices, and the table containing the application bindings. Also, if security is used, some information like the frame counters will be stored.

This information is used to restore the device in the network if the device is reset. In `ZDApp_Init()`, a call to `NLME_RestoreFromNV()` instructs the network layer to restore its network state from values stored in NV. This function call will also initialize the NV space needed for the network layer if the space isn’t already established.

9.6.3 Application Non-Volatile Memory

NV can also be used to save information specific to the application and the User Descriptor is a good example. The NV item ID for the User Descriptor is `ZDO_NV_USERDESC` (defined in ZComDef.h).

In `ZDApp_InitUserDesc()`, which is called from `ZDApp_Init()`, `osal_nv_item_init()` is called to initialize the NV space needed for the User Descriptor. If this is the first time that this function is called for this NV item, the init function will reserve the space for the User Descriptor and set the default value to `ZDO_DefaultUserDescriptor`.
Then when the NV stored User Descriptor is needed, as in `ZDO_ProcessUserDescReq()`, in `ZDObject.c`, it calls `osal_nv_read()` to get the User Descriptor from NV.

To update the User Descriptor in NV, as in `ZDO_ProcessUserDescSet()`, in `ZDObject.c`, it calls `osal_nv_write()` to set the updated User Descriptor in NV.

Remember: the NV items are each unique and if your application creates its own NV item is must select an ID from the application value range (0x0401 – 0x0FFF).

9.7 Asynchronous Links

An asynchronous link occurs when a node can receive packets from another node but it can't send packets to that node. Whenever this happens, this link is not a good link to route packets.

In ZigBee PRO, this problem is overcome by the use of the Network Link Status message. Every router in a ZigBee PRO network sends a periodic Link Status message. This message is a one hop broadcast message that contains the sending device's neighbor list. The idea is this – if you receive your neighbor's Link Status and you are either missing from the neighbor list or your receive cost is too low (in the list), you can assume that the link between you and this neighbor is an asynchronous link and you should not use it for routing.

To change the time between Link Status messages you can change the compile flag `NWK_LINK_STATUS_PERIOD`, which is used to initialize `_NIB.nwkLinkStatusPeriod`. You can also change `_NIB.nwkLinkStatusPeriod` directly. Remember that only PRO routers send the link status message and that every router in the network must have the same Link Status time period.

`_NIB.nwkLinkStatusPeriod` contains the number of seconds between Link Status messages.

Another parameter that affects the Link Status message is `_NIB.nwkRouterAgeLimit` (defaulted to `NWK_ROUTE_AGE_LIMIT`). This represents the number of Link Status periods that a router can remain in a device's neighbor list, without receiving a Link Status from that device, before it becomes aged out of the list. If we haven't received a Link Status message from a neighbor within (`_NIB.nwkRouterAgeLimit * _NIB.nwkLinkStatusPeriod`), we will age the neighbor out and assume that this device is missing or that it's an asynchronous link and not use it.

9.8 Multicast Messages

This feature is a ZigBee PRO only feature (must have `ZIGBEEPRO` as a compile flag). This feature is similar to sending to an APS Group, but at the network layer.

A multicast message is sent from a device to a group as a MAC broadcast message. The receiving device will determine if it is part of that group: if it isn't part of the group, it will decrement the non-member radius and rebroadcast; if it is part of the group it will first restore the group radius and then rebroadcast the message. If the radius is decremented to 0, the message isn't rebroadcast.

The difference between multicast and APS group messages can only be seen in very large networks where the non-member radius will limit the number of hops away from the group.

`_NIB.nwkUseMultiCast` is used by the network layer to enable multicast (default is `TRUE` if `ZIGBEEPRO` defined) for all Group messages, and if this field is `FALSE` the APS Group message is sent as a normal broadcast network message.

`zgApsNonMemberRadius` is the value of the group radius and the non-member radius. This variable should be controlled by the application to control the broadcast distribution. If this number is too high, the effect will be the same as an APS group message. This variable is defined in `ZGlobals.c` and `ZCD_NV_APS_NONMEMBER_RADIUS` (defined in `ZComDef.h`) is the NV item.

9.9 Fragmentation

Message Fragmentation is a process where a large message – too large to send in one APS packet – is broken down and transmitted as smaller fragments. The fragments of the larger message are then reassembled by the receiving device.

To turn on the APS Fragmentation feature in your Z-Stack project include the `ZIGBEE_FRAGMENTATION` compile flag. By default, all projects where ZIGBEEPRO is defined include fragmentation and there is no need to add the `ZIGBEE_FRAGMENTATION` compile flag. All applications using fragmentation will include the APS Fragmentation task `APSF_Init()` and `APSF_ProcessEvent()`. If you have an existing application, make sure the code in the OSAL_xxx.c of your application has included the header file:

```
#if defined ( ZIGBEE_FRAGMENTATION )
  #include "aps_frag.h"
#endif
```

And in `tasksArr[]` there is an entry for `APSF_ProcessEvent()`, like in the example below:

```
const pTaskEventHandlerFn tasksArr[] = {
  macEventLoop,
  nwk_event_loop,
  Hal_ProcessEvent,
#if defined( MT_TASK )
  MT_ProcessEvent,
#endif
  APS_event_loop,
#if defined ( ZIGBEE_FRAGMENTATION )
  APSF_ProcessEvent,
#endif
  ZDApp_event_loop,
#if defined ( ZIGBEE_FREQ_AGILITY ) || defined ( ZIGBEE_PANID_CONFLICT )
  ZDNwkMgr_event_loop,
#endif
  xxx_ProcessEvent          /* Where xxx is your application’s name */
};
```

And `osalInitTasks()` function calls `APSF_Init()`, like in the code below;

```
void osalInitTasks( void )
{
  uint8 taskID = 0;

  tasksEvents = (uint16 *)osal_mem_alloc( sizeof( uint16 ) * tasksCnt);
  osal_memset( tasksEvents, 0, (sizeof( uint16 ) * tasksCnt));

  macTaskInit( taskID++ );
  nwk_init( taskID++ );
  Hal_Init( taskID++ );
#if defined( MT_TASK )
  MT_TaskInit( taskID++ );
#endif
  APS_Init( taskID++ );
#if defined ( ZIGBEE_FRAGMENTATION )
  APSF_Init( taskID++ );
#endif
  ZDApp_Init( taskID++ );
#if defined ( ZIGBEE_FREQ_AGILITY ) || defined ( ZIGBEE_PANID_CONFLICT )
  ZDNwkMgr_Init( taskID++ );
#endif
  xxx_Init( taskID );       /* Where xxx is your application’s name */
}
```

When APS Fragmentation is turned on, sending a data request with a payload larger than a normal data request payload will automatically trigger fragmentation.

Fragmentation parameters are in the structure `afAPSF_Config_t`, which is part of the Endpoint Descriptor list `epList_t` defined in `AF.h`, default values for these parametes are used when calling `afRegister()`, to register the Application's Endpoint Descriptor, which in turn calls `afRegisterExtended()`, the default values `APSF_DEFAULT_WINDOW_SIZE` and `APSF_DEFAULT_INTERFRAME_DELAY` are defined in `ZGlobals.h`:

- `APSF_DEFAULT_WINDOW_SIZE` - The size of a Tx window when using fragmentation. This is the number of fragments that are sent before an APS Fragmentation ACK is expected. So, if the message is broken up into 10 fragments and the max window size is 5, then an ACK will be sent by the receiving device after 5 fragments are received. If one packet of the window size isn't received, the ACK is not sent and all the packets (within that window) are resent.
- `APSF_DEFAULT_INTERFRAME_DELAY` – The delay between fragments within a window. This is used by the sending device.

These values can be read and set by the application by calling `afAPSF_ConfigGet()` and `afAPSF_ConfigSet()` respectively.

It is recommended that the application/profile update the `MaxInTransferSize` and `MaxOutTransferSize` of the ZDO Node Descriptor for the device, `ZDConfig_UpdateNodeDescriptor()` in `ZDConfig.c`. These fields are initialized with `MAX_TRANSFER_SIZE` (defined in `ZDConfig.h`). These values are not used in the APS layer as maximums, they are information only.

9.9.1 Quick Reference

Compile flag to activate the feature	`ZIGBEE_FRAGMENTATION`
Maximum fragments in a window default value	`APSF_DEFAULT_WINDOW_SIZE` (defined in `ZGlobals.h`)
Interframe delay default value	`APSF_DEFAULT_INTERFRAME_DELAY` (defined in `ZGlobals.h`)
Application/Profile maximum buffer size	`MAX_TRANSFER_SIZE` (defined in `ZDConfig.h`)

9.10 Extended PAN IDs

There are two Extended PAN IDs used in the Z-Stack:

- `zgApsUseExtendedPANID`: This is the 64-bit PAN identifier of the network to join or form. This corresponds to the `ZCD_NV_APS_USE_EXT_PANID` NV item.
- `zgExtendedPANID`: This is the 64-bit extended PAN ID of the network to which the device is joined. If it has a value of 0x0000000000000000, then the device is not connected to a network. This corresponds to the `ZCD_NV_EXTENDED_PAN_ID` NV item.

When a device starts up, it checks the value of `zgExtendedPANID`. If `zgExtendedPANID` has a non-zero value, then the device assumes it has all the network parameters required to operate on a network.

If the device finds it is not connected to a network, then it checks to see if it's configured to become a ZigBee Coordinator. If it's configured as a coordinator, then it will form a network using `zgApsUseExtendedPANID` if `zgApsUseExtendedPANID` has a non-zero value. If `zgApsUseExtendedPANID` is 0x0000000000000000, then the device will use its 64-bit Extended Address to form the network.

When the device is not the designated coordinator and `zgApsUseExtendedPANID` has a non-zero value, then it will attempt to rejoin the network specified in `zgApsUseExtendedPANID`. The device will join only the specified network and the procedure will fail if that network is found to be inaccessible. If `zgApsUseExtendedPANID` is equal to 0x0000000000000000, then the device will join the best available network.

9.11 Rejoining with Pre-Commissioned Network address

During network rejoining process a device that needs to be deployed with a predefined network address shall have configured the `zgApsUseExtendedPANID` and the `zgNwkCommissionedNwkAddr`, this corresponds to the `ZCD_NV_COMMISSIONED_NWK_ADDR` NV item.

If configuration element `zgNwkCommissionedNwkAddr` has a valid short address value during the rejoin process, the device will put it in the `_NIB.nwkDevAddress` and use that in the Rejoin Request, otherwise it will randomly generate the short address and use it in the Rejoin Request.

10. Security

10.1 Overview

ZigBee security is built with the AES block cipher and the CCM* mode of operation as the underlying security primitive. AES/CCM* security algorithms were developed by external researchers outside of ZigBee Alliance and are also used widely in other communication protocols.

ZigBee offers the following security features:

- Infrastructure security
- Network access control
- Application data security

10.2 Configuration

In order to have a secure network, first all device images must be built with the preprocessor flag `SECURE` set equal to 1. This can be found in the `f8wConfig.cfg` file.

The default key (`defaultKey` in `nwk_globals.c`) can be preconfigured on each device in the network or it can be configured only on the coordinator and distributed to each device over-the-air as it joins the network. This is chosen via the z`gPreConfigKeys` option in `ZGlobals.c` file. If it is set to `TRUE`, then the value of default key must be preconfigured on each device (to the exact same value). If it is set to `FALSE`, then the default key parameter needs to be set only on the coordinator device. Note that in the latter case, the key will be distributed to each joining device over-air. So there is a *"moment of vulnerability"* during the joining process during which an adversary can determine the key by listening to the on-air traffic and compromise the network security.

10.3 Network access control

In a secure network, the Trust Center (coordinator) is informed when a device joins the network. The coordinator has the option of allowing that device to remain on the network or denying network access to that device.

The Trust Center may use any logic to determine if the device should be allowed into the network or not. One option is for the Trust Center to only allow devices to join during a brief time window. This may be possible, for example, if the Trust Center has a "push" button. When the button is pressed, it could allow any device to join the network for a brief time window. Otherwise all join requests would be rejected. A second possible scenario would be to configure the trust center to accept (or reject) devices based on their IEEE addresses.

This type of policy can be realized by modifying the `ZDSecMgrDeviceValidate()` function found in the `ZDSecMgr.c` module.

10.4 Key Updates

The Trust Center can update the common Network key at its discretion. Application developers have to modify the Network key update policy. The default Trust Center implementation can be used to suit the developer's specific policy. An example policy would be to update the Network key at regular periodic intervals. Another would be to update the NWK key upon user input (like a button-press). The ZDO Security Manager `ZDSecMgr.c` API provides this functionality via `ZDSecMgrUpdateNwkKey()` and `ZDSecMgrSwitchNwkKey()`. `ZDSecMgrUpdateNwkKey()` allows the Trust Center to send a new Network key to the `dstAddr` on the network. At this point the new Network key is stored as an alternate key in the destination device or devices if `dstAddr` was a broadcast address. Once the Trust Center calls `ZDSecMgrSwitchNwkKey()`, with the `dstAddr` of the device or devices, if broadcast, all destination devices will use their alternate key.

10.5 Trust Center Link Key

The ZigBee Alliance defines a default link key *ZigBeeAlliance09* in [1]. Its value is defined as `DEFAULT_TC_LINK_KEY` in `nwk_globals.h`. A different value could be used if required by the application and/or profile.

There are two types of Link Keys that can be used in a network: UNIQUE and GLOBAL. The type of Link Key used by the local device will determine how APS commands are handled as well the encryption used for those messages.

To enable all TCLK processing code, either the `TC_LINKKEY_JOIN` or the `SE_PROFILE` compiler flag shall be defined in the project. The application can control the type of Link Key by setting `zgApsLinkKeyType`, in `ZGlobals.h`, to value `ZG_GLOBAL_LINK_KEY` or `ZG_UNIQUE_LINK_KEY`. The corresponding NV item for `zgApsLinkKeyType is ZCD_NV_APS_LINK_KEY_TYPE`.

10.6 Joining a Network with TCLK

For devices that want to join a network that is using Trust Center Link Key, it is required that all devices have a pre-configured Trust Center Link Key (TCLK) and that the network key is delivered to joining devices secured with that link key. There are basically 2 joining scenarios for a joining device:

10.6.1 Multi-hop

When a device joins the network, but its parent isn't the Trust Center, the transport key command is tunneled from the Trust Center, through the parent of the joining device, to the joining device. The joining procedure is illustrated in the following figures. Notice that the APS Update Device command sent from the parent to the trust center will be encrypted according to the `zgApsLinkKeyType` configuration and using the highest APS security level. The APS Tunnel Command with APS Transport Key command as the payload is network layer encrypted but the payload is APS layer encrypted with the trust center link key between the trust center and the joining device. Finally, The APS Transport Key command forwarded from the parent to the joining device is APS encrypted with the trust center link key between the trust center and the joining device.

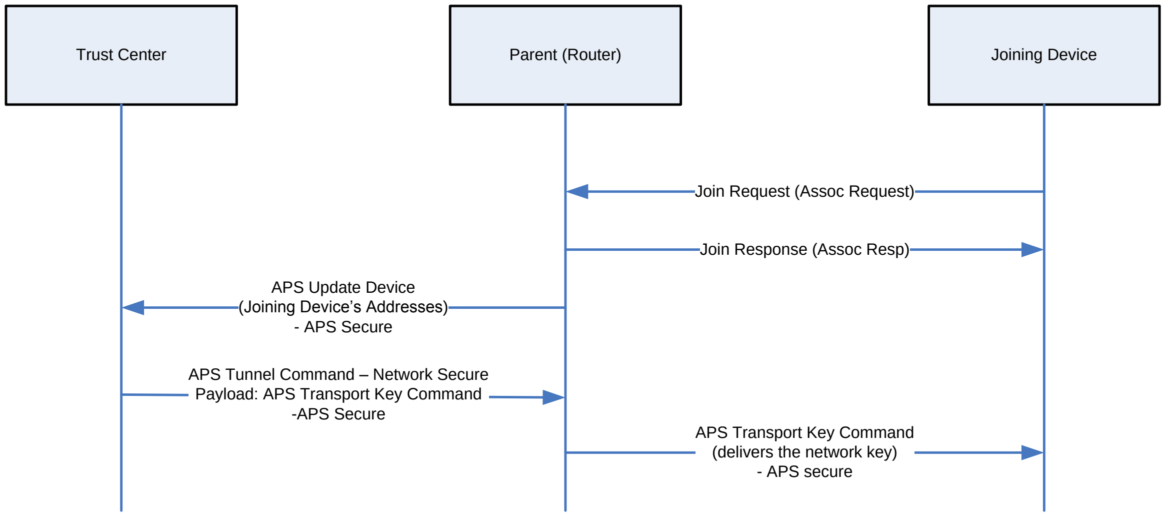

Trust Center
Parent (Router)
Joining Device
Join Request (Assoc Request)
Join Response (Assoc Resp)
APS Update Device
(Joining Device's Addresses)
- APS Secure
APS Tunnel Command – Network Secure
Payload: APS Transport Key Command
-APS Secure
APS Transport Key Command
(delivers the network key)
- APS secure

Figure 5: Unique Link Key Type – Joining when parent is not the Trust Center

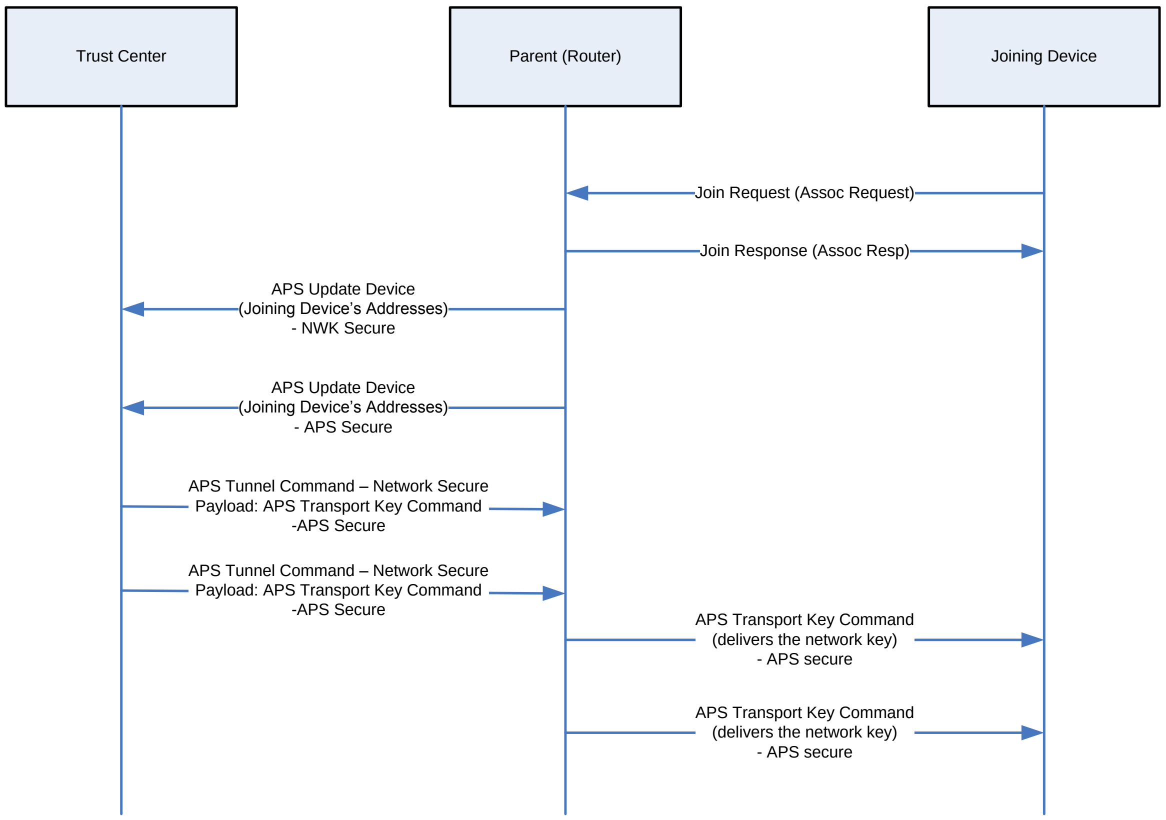

Trust Center
Parent (Router)
Joining Device
Join Request (Assoc Request)
Join Response (Assoc Resp)
APS Update Device (Joining Device's Addresses) - NWK Secure
APS Update Device (Joining Device's Addresses) - APS Secure
APS Tunnel Command – Network Secure Payload: APS Transport Key Command -APS Secure
APS Tunnel Command – Network Secure Payload: APS Transport Key Command -APS Secure
APS Transport Key Command (delivers the network key) - APS secure
APS Transport Key Command (delivers the network key) - APS secure

Figure 6: Global Link Key Type – Joining when parent is not the Trust Center

10.6.2 Single-hop

When a device joins the network, and its parent is the Trust Center, the transport key command is encrypted with the pre-configured Trust Center Link key.

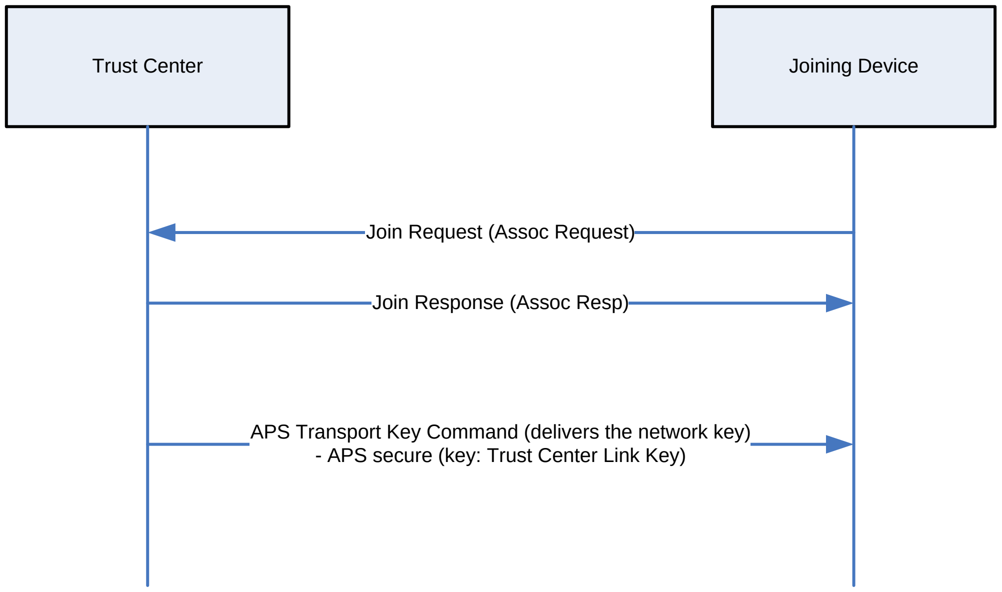

Trust Center
Joining Device
Join Request (Assoc Request)
Join Response (Assoc Resp)
APS Transport Key Command (delivers the network key) - APS secure (key: Trust Center Link Key)

Figure 7: Global/Unique Link Key Type – Joining when parent is the Trust Center

To enable the TCLK Joining feature, set `SECURE=1` in `f8wConfig.cfg` and include the `TC_LINKKEY_JOIN` or the `SE_PROFILE` compile flag. There are other associated compiler flags, global variables (ZGlobals) and NV Items.

If `zgApsLinkKeyType` is set to `ZG_UNIQUE_LINK_KEY`, unique pre-configured trust center link keys are used between the Trust Center and each individual device joining the network. If `zgApsLinkKeyType` is set to `ZG_GLOBAL_LINK_KEY`, all devices are using the same pre-configured trust center link key to join the network. The Global Link Key Type provides a simplified alternative procedure to set up the network.

To start the network using Unique Link Key Type:

- Set `zgApsLinkKeyType` = `ZG_UNIQUE_LINK_KEY` (defined in `ZGlobals.c`), variable `zgUseDefaultTCLK` is set internally depending of this value. The NV item for these global variables are `ZCD_NV_APS_LINK_KEY_TYPE` and `ZCD_NV_USE_DEFAULT_TCLK` (defined in `ZComDef.h`).
- Set compile time option ZDSECMGR_TC_DEVICE_MAX to the maximum number of devices joining the network. Notice that it has to be no more than 255, as only 255 continuous NV ID space is reserved for preconfigured trust center link keys.
- All preconfigured trust center links keys are stored as separate NV items. The NV item ids range from `ZCD_NV_TCLK_TABLE_START` to `ZCD_NV_TCLK_TABLE_START+ ZDSECMGR_TC_DEVICE_MAX-1`. Preconfigured trust center link keys are set by configuring the NV items using SYS_OSAL_NV_WRITE for the attributes listed below:

Attribute	Description	Value
Id	NV ID for the trust center link key.	`ZCD_NV_TCLK_TABLE_START` plus an offset.
Len	Length in bytes of the item.	0x20
Offset	The memory offset into the NV item.	0x0
Value	The data array to be written to the NV item.	Its byte format is listed in the following table. All fields follow little endian first.

Table for byte format of NV item value:

Length	8 Octets	16 Octets	4 Octets	4 Octets
Attribute Field	Extended Address	Key Data	Tx Frame Counter	Rx Frame Counter
Description	Extended Address of the peer devices which shares the preconfigured tclk	The preconfigured trust center link key data	The Tx frame counter of the trust center link key	The Rx frame counter of the trust center link key

- To remove a preconfigured trust center link key, simply write all zeros to the NV item.
- It is highly recommended to erase the entire flash before using Unique Link Keys to make sure there is no existing NV item for the preconfigured trust center link keys.

To start the network using Global Link Key Type:

- Set `zgApsLinkKeyType = ZG_GLOBAL_LINK_KEY` (defined in `ZGlobals.c`), variable `zgUseDefaultTCLK` is set internally depending of this value. The NV item for these global variables are `ZCD_NV_APS_LINK_KEY_TYPE` and `ZCD_NV_USE_DEFAULT_TCLK` (defined in `ZComDef.h`).
- The default preconfigured trust center link key is written to NV item `ZCD_NV_TCLK_TABLE_START` if it has not been initialized yet. To differentiate the default preconfigured trust center link key, the extended address for default preconfigured trust center link key is all 0xFFs. The key data is initialized with

`defaultTCLinkKey` (defined in `nwk_globals.c`). The Rx and Tx frame counters are initialized to all zeros.

- The default preconfigured TCLK can be changed by changing the key data, Rx and Tx frame counter fields in the NV item directly.
- It is highly recommended to erase the entire flash before using the Global Link Key Type to make sure there is no existing NV item for the default preconfigured trust center link key.
- To remove the default preconfigured trust center link key, simply write all zeros to that NV item.

Please note that the Unique Link Key and Global Link Key shall be used exclusively.

10.7 Security key data management

Management and access of security keys in NV through MT commands is disabled by default. In order to have access to security key data, the compiler flag `MT_SYS_KEY_MANAGEMENT` must be included in the project. ***It is highly recommended to disable this compiler flag for production devices***, to prevent any potential vulnerability that comes from having direct access to security key data in NV.

NV IDs for security keys are defined in `ZComDef.h` and summarized in the table below. Active and Alternate Network keys are defined as individual items, while Trust Center, Application and Master keys each reserve a range of NV IDs, allowing up to 255 keys of each type.

Value	**NV ID**	**Description**
`ZCD_NV_NWK_ACTIVE_KEY_INFO`	0x003A	Active Network key
`ZCD_NV_NWK_ALTERN_KEY_INFO`	0x003B	Alternate Network Key
`ZCD_NV_TCLK_TABLE_START`	0x0101	First element of TCLK table
`ZCD_NV_TCLK_TABLE_END`	0x01FF	Last element of TCLK table
`ZCD_NV_APS_LINK_KEY_DATA_START`	0x0201	First element of APS Link Key table
`ZCD_NV_APS_LINK_KEY_DATA_END`	0x02FF	Last element of APS Link Key table
`ZCD_NV_MASTER_KEY_DATA_START`	0x0301	First element of Master Key table
`ZCD_NV_MASTER_KEY_DATA_END`	0x03FF	Last element of Master Key table

10.8 Backwards Interoperability

There is a known interoperability issue when Unique Link Key Type is used and the Trust Center, running R20 Z-Stack, is in a network with older devices (R19). In version 20 of the ZigBee Specification [1] it is required that the Trust Center only allow APS command messages APS encrypted, but ZigBee Routers running older versions of Z-Stack send APS command messages (like Update Device) NWK encrypted only. To overcome that issue, there is a configuration control item. `zgApsAllowR19Sec` defined in `ZGlobals.c`, that the application can set to allow R19 devices to join the network. The corresponding NV item is `ZCD_NV_APS_ALLOW_R19_SECURITY` defined in `ZComDef.h`.

10.9 Quick Reference

Enabling security	Set `SECURE` = 1 (in `f8wConfig.cfg`)
Enabling preconfigured Network key	Set `zgPreConfigKeys = TRUE` (in `ZGlobals.c`)
Setting preconfigured Network key	Set `defaultKey` = {KEY} (in `nwk_globals.c`)

Enabling/disabling joining permissions on the Trust Center	Call `ZDSecMgrPermitJoining()` (in `ZDSecMgr.c`)
Specific device validation during joining	Modify `ZDSecMgrDeviceValidate` (in `ZDSecMgr.c`)
Network key updates	Call `ZDSecMgrUpdateNwkKey()` and `ZDSecMgrSwitchNwkKey()` (in `ZDSecMgr.c`)
Enabling Pre-Configured Trust Center Link Keys	Set `SECURE = 1` (in `f8wConfig.cfg`) and include `TC_LINKKEY_JOIN` or `SE_PROFILE` as a compile flag.
Use Global Trust Center Link Key	Set `zgApsLinkKeyType` = `ZG_GLOBAL_LINK_KEY` (in `ZGlobals.c`). The NV item for this global is `ZCD_NV_APS_LINK_KEY_TYPE` (defined in `ZComDef.h`).
Use Unique Trust Center Link Keys	Set `zgApsLinkKeyType` = `ZG_UNIQUE_LINK_KEY` (in `ZGlobals.c`). The NV item for this global is `ZCD_NV_APS_LINK_KEY_TYPE` (in `ZComDef.h`). Configure a preconfigured trust center link key for each device joining the network via SYS_OSAL_NV_WRITE.

11. Network Manager

11.1 Overview

A single device can become the Network Manager. This device acts as the central mechanism for reception of network:

- Channel Interference reports and changing the channel of the network if interference is detected, and
- PAN ID Conflict reports and changing the PAN ID of the network if conflict is detected.

The default address of the Network Manager is the coordinator. However, this can be updated by sending a *Mgmt_NWK_Update_req* command with a different short address for the Network Manager. The device that is the Network Manager sets the network manager bit in the server mask in the node descriptor and responds to *System_Server_Discovery_req* commands.

The Network Manager implementation resides in `ZDNwkMgr.c` and `ZDNwkMgr.h` files.

11.2 Channel Interference

The Network Manager implements frequency agility measures in the face of interference. This section explains how, through the use of the *Mgmt_NWK_Update_req* and *Mgmt_NWK_Update_notify* commands, the channel of a network can be changed.

11.2.1 Channel Interference Detection

Each router or coordinator tracks transmit failures using the Transmit Failure field in the neighbor table and also keeping a NIB counter for Total Transmissions attempted. Once the total transmissions attempted is over `ZDNWKMGR_MIN_TRANSMISSIONS` (20), if the transmit failures exceeds `ZDNWKMGR_CI_TX_FAILURE` (25) percent of the messages sent, the device may have detected interference on the channel in use.

The device then takes the following steps:

1. Conduct an energy scan on all channels. If this energy scan does not indicate higher energy on the current channel than other channels, no action is taken. The device should continue to operate as normal and the message counters are not reset.
2. If the energy scan does indicate increased energy on the channel in use, a *Mgmt_NWK_Update_notify* should be sent to the Network Manager to indicate interference is present. This report is sent as an APS unicast with acknowledgement and once the acknowledgment is received the total transmit and transmit failure counters are reset to zero.
3. To avoid a device with communication problems from constantly sending reports to the Network Manager, the device does not send a *Mgmt_NWK_Update_notify* more than 4 times per hour.

11.2.2 Channel Interference Resolution

Upon receipt of an unsolicited *Mgmt_NWK_Update_notify*, the Network Manager applies different methods to best determine when a channel change is required and how to select the most appropriate channel.

The Network Manger does the following:

1. Upon receipt of the *Mgmt_NWK_Update_notify*, the Network Manager determines if a channel change is required using the following criteria:
    a. If any single device has more than `ZDNWKMGR_CC_TX_FAILURE` (50) percent transmission failures a channel change should be considered.
    b. The Network Manager compares the failure rate reported on the current channel against the stored failure rate from the last channel change. If the current failure rate is higher than the last failure rate then the channel change is considered.
2. If the above data indicate a channel change should be considered, the Network Manager completes the following:

   a. Select a single channel based on the *Mgmt_NWK_Update_notify* based on the lowest energy. This is the proposed new channel. If this new channel does not have an energy level below an acceptable threshold `ZDNWKMGR_ACCEPTABLE_ENERGY_LEVEL`, a channel change should not be done.

3. Prior to changing channels, the Network Manager stores the energy scan value as the last energy scan value and the failure rate from the existing channel as the last failure rate.
4. The Network Manager broadcasts (to all routers and coordinator) a *Mgmt_NWK_Update_req* notifying devices of the new channel. It then increments the *nwkUpdateId* parameter in the NIB and beacon payload, and includes it in the *Mgmt_NWK_Update_req*. The Network Manager sets a timer based on the value of `ZDNWKMGR_UPDATE_REQUEST_TIMER` (i.e., *apsChannelTimer*) upon issue of a *Mgmt_NWK_Update_req* that changes channels and will not issue another such command until this timer expires.
5. Upon issue of a *Mgmt_NWK_Update_req* with a change of channels, the local Network Manager sets a timer equal to the *nwkNetworkBroadcastDeliveryTime* and switches channels upon expiration of this timer.

Upon receipt of a *Mgmt_NWK_Update_req* with a change of channels from the Network Manager, a device sets a timer equal to the *nwkNetworkBroadcastDeliveryTime* and switches channels upon expiration of this timer. Each node stores the received *nwkUpdateId* in the NIB and beacon payload, and also resets the total transmit count and the transmit failure counters.

For devices with *RxOnWhenIdle* equals FALSE, any network channel change will not be received. On these devices or routers that have lost the network, an active scan is conducted on the *channelList* in the NIB (i.e., *apsChannelMask*) using the extended PAN ID (EPID) to find the network. If the extended PAN ID is found on different channels, the device selects the channel with the higher value in the *nwkUpdateId* parameter. If the extended PAN ID is not found using the *apsChannelMask* list, a scan is completed using all channels.

11.2.3 Quick Reference

Setting minimum transmissions attempted for Channel Interference detection	Set `ZDNWKMGR_MIN_TRANSMISSIONS` (in `ZDNwkMgr.h`)
Setting minimum transmit failure rate for Channel Interference detection	Set `ZDNWKMGR_CI_TX_FAILURE` (in `ZDNwkMgr.h`)
Setting minimum transmit failure rate for Channel Change	Set `ZDNWKMGR_CC_TX_FAILURE` (in `ZDNwkMgr.h`)
Setting acceptable energy level threshold for Channel Change	Set `ZDNWKMGR_ACCEPTABLE_ENERGY_LEVEL` (in `ZDNwkMgr.h`)
Setting APS channel timer for issuing Channel Changes	Set `ZDNWKMGR_UPDATE_REQUEST_TIMER` (in `ZDNwkMgr.h`)

11.3 PAN ID Conflict

Since the 16-bit PAN ID is not a unique number there is a possibility of a PAN ID conflict in the local neighborhood. The Network Manager implements PAN ID conflict resolution. This section explains how, through the use of the Network Report and Update commands, the PAN ID of a network can be updated.

11.3.1 PAN ID Conflict Detection

Any device that is operational on a network and receives a beacon in which the PAN ID of the beacon matches its own PAN ID but the EPID value contained in the beacon payload is either not present or not equal to *nwkExtendedPANID*, is considered to have detected a PAN ID conflict.

A node that has detected a PAN ID conflict sends a Network Report command of type PAN ID conflict to the designated Network Manager identified by the *nwkManagerAddr* in the NIB. The Report Information field will contain a list of all the 16-bit PAN identifiers that are being used in the local neighborhood. The list is constructed from the results of an ACTIVE scan.

11.3.2 PAN ID Conflict Resolution

On receipt of the Network Report command, the Network Manager selects a new 16-bit PAN ID for the network. The new PAN ID is chosen at random, but a check is performed to ensure that the chosen PAN ID is not contained within the Report Information field of the network report command.

Once a new PAN ID has been selected, the Network Manager first increments the NIB attribute *nwkUpdateID* and then constructs a Network Update command of type PAN identifier update. The Update Information field is set to the value of the new PAN ID. After it sends out this command, the Network Manager starts a timer with a value equal to *nwkNetworkBroadcastDeliveryTime* seconds. When the timer expires, it changes its current PAN ID to the newly selected one.

On receipt of a Network Update command of type PAN ID update from the Network Manager, a device (in the same network) starts a timer with a value equal to *nwkNetworkBroadcastDeliveryTime* seconds. When the timer expires, the device changes its current PAN ID to the value contained within the Update Information field. It also stores the new received *nwkUpdateID* in the NIB and beacon payload.

12. Inter-PAN Transmission

12.1 Overview

Inter-PAN transmission enables ZigBee devices to perform limited, insecure, and possibly anonymous exchange of information with devices in their local neighborhood without having to form or join the same ZigBee network.

The Inter-PAN feature is implemented by the Stub APS layer, which can be included in a project by defining the `INTER_PAN` compile option and including `stub_aps.c` and `stub_aps.h` files in the project.

12.2 Data Exchange

Inter-PAN data exchanges are handled by the Stub APS layer, which is accessible through INTERP-SAP, parallel to the normal APSDE-SAP:

- The `INTERP_DataReq()` and `APSDE_DataReq()` are invoked from `AF_DataRequest()` to send Inter-PAN and Intra-PAN messages respectively.
- The `INTERP_DataIndication()` invokes `APSDE_DataIndication()` to indicate the transfer of Inter-PAN data to the local application layer entity. The application then receives Inter-PAN data as a normal incoming data message (`APS_INCOMING_MSG`) from the APS sub-layer with the source address belonging to an external PAN (verifiable by `StubAPS_InterPan()` API) .
- The `INTERP_DataConfirm()` invokes `afDataConfirm()` to send an Inter-PAN data confirm back to the application. The application receives a normal data confirm (`AF_DATA_CONFIRM_CMD`) from the AF sub-layer.

The Stub APS layer also provides interfaces to switch channel for Inter-PAN communication and check for Inter-PAN messages. Please refer to the Z-Stack API [2] document for detailed description of the Inter-PAN APIs.

The `StubAPS_InterPan()` API is used to check for Inter-PAN messages. A message is considered as an Inter-PAN message if it meets one the following criteria:

- The current communication channel is different that the device's NIB channel, or
- The current communication channel is the same as the device's NIB channel *but* the message is destined for a PAN different than the device's NIB PAN ID, or
- The current communication channel is the same as the device's NIB channel *and* the message is destined for the same PAN as device's NIB PAN ID *but* the destination application endpoint is an Inter-PAN endpoint (`0xFE`). This case is true for an Inter-PAN response message that's being sent back to a requestor.

A typical usage scenario for Inter-PAN communication is as follows. The initiator device:-

- Calls `StubAPS_AppRegister()` API to register itself with the Stub APS layer
- Calls `StubAPS_SetInterPanChannel()` API to switch its communication channel to the channel in use by the remote device
- Specifies the destination PAN ID and address for the Inter-PAN message about to be transmitted
- Calls `AF_DataRequest()` API to send the message to the remote device through Inter-PAN channel
- Receives back (if required) a message from the remote device that implements the Stub APS layer and is able to respond
- Calls `StubAPS_SetIntraPanChannel()` API to switch its communication channel back to its original channel

12.2.1 Quick Reference

Setup application as InterPAN application.	Call `StubAPS_RegisterApp( app_endpoint )`
Set InterPAN channel.	Call `StubAPS_SetInterPanChannel( channel )`
Send InterPAN Message.	Call `AF_DataRequest()` with: • dstPanID different from `_NIB.nwkPanId` • dst address endpoint == `STUBAPS_INTER_PAN_EP`
Receive an InterPAN message.	Receive an `OSAL AF_INCOMING_MSG_CMD` message with an incoming DstEndPoint == `STUBAPS_INTER_PAN_EP`
End the InterPAN session by putting back the IntraPAN channel.	Call `StubAPS_SetIntraPanChannel()`

13. ZMAC LQI Adjustment

13.1 Overview

The IEEE 802.15.4 specification provides some general statements on the subject of LQI. From section 6.7.8: "The minimum and maximum LQI values (0x00 and 0xFF) should be associated with the lowest and highest IEEE 802.15.4 signals detectable by the receiver, and LQI values should be uniformly distributed between these two limits." From section E.2.3: "The LQI (see 6.7.8) measures the received energy and/or SNR for each received packet. When energy level and SNR information are combined, they can indicate whether a corrupt packet resulted from low signal strength or from high signal strength plus interference."

The TI MAC computes an 8-bit “link quality index” (LQI) for each received packet from the 2.4 GHz radio. The LQI is computed from the raw “received signal strength index” (RSSI) by linearly scaling it between the minimum and maximum defined RF power levels for the radio. This provides an LQI value that is based entirely on the strength of the received signal. This can be misleading in the case of a narrowband interferer that is within the channel bandwidth – the RSSI may be increased even though the true link quality decreases.

The TI radios also provide a “correlation value” that is a measure of the received frame quality. Although not considered by the TI MAC in LQI calculation, the frame correlation is passed to the ZMAC layer (along with LQI and RSSI) in MCPS data confirm and data indication callbacks. The `ZMacLqiAdjust()` function in `zmac_cb.c` provides capability to adjust the default TI MAC value of LQI by taking the correlation into account.

13.2 LQI Adjustment Modes

LQI adjustment functionality for received frames processed in `zmac_cb.c` has three defined modes of operation - *OFF*, *MODE1*, and *MODE2*. To maintain compatibility with previous versions of Z-Stack which do not provide for LQI adjustment, this feature defaults to *OFF*, as defined by an initializer (`lqiAdjMode = LQI_ADJ_OFF;`) in `zmac_cb.c` – developers can select a different default state by changing this statement.

MODE1 provides a simple algorithm to use the packet correlation value (related to SNR) to scale incoming LQI value (related to signal strength) to 'de-rate' noisy packets. The incoming LQI value is linearly scaled with a "correlation percentage" that is computed from the raw correlation value between theoretical minimum/maximum values (`LQI_CORR_MIN` and `LQI_CORR_MAX` are defined in `ZMAC.h`).

MODE2 provides a “stub” for developers to implement their own proprietary algorithm. Code can be added after the “`else if ( lqiAdjMode == LQI_ADJ_MODE2 )`” statement in `ZMacLqiAdjust()`.

13.3 Using LQI Adjustment

There are two ways to enable the LQI adjustment functionality:

(1) Alter the initialization of the `lqiAdjMode` variable as described in the previous section
(2) Call the function `ZMacLqiAdjustMode()` from somewhere within the Z-Stack application, most likely from the application’s task initialization function. See the Z-Stack API [2] document on details of this function.

The `ZMacLqiAdjustMode()` function can be used to change the LQI adjustment mode as needed by the application. For example, a developer might want to evaluate device/network operation using a proprietary *MODE2* compared to the default *MODE1* or *OFF*.

Tuning of *MODE1* operation can be achieved by altering the values of LQI_CORR_MIN and/or LQI_CORR_MAX. When using IAR development tools, alternate values for these parameters can be provided as compiler directives in the IDE project file or in one of Z-Stack’s .cfg files (`f8wConfig.cfg`, `f8wCoord.cfg`, etc.). Refer to the radio’s data sheet for information on the normal minimum/maximum correlation values.

14. Heap Memory Management

14.1 Overview

The OSAL heap memory manager provides a POSIX-like API for allocating and re-cycling dynamic heap memory. Two important considerations in a low-cost, resource-constrained embedded system, size and speed, have been duly addressed in the implementation of the heap memory manager.

- Overhead memory cost to manage each allocated block has been minimized – as little as *2 bytes* on CPU's with one- or two-byte-aligned memory access (e.g. 8051 SOC and MSP430).
- Interrupt latency for the allocation and free operations has been minimized – freeing is immediate with no computational load other than bounds checks and clearing a bit; allocating is very much sped-up with a packed long-lived memory block and a dynamically updated first-free pointer for high-frequency small-block allocations (e.g. OSAL Timers).

14.2 API

14.2.1 osal_mem_alloc()

The `osal_mem_alloc()` function is a request to the memory manager to reserve a block of the heap.

14.2.1.1 Prototype

```
void *osal_mem_alloc( uint16 size );
```

14.2.1.2 Parameters

`size` – the number of bytes of dynamic memory requested.

14.2.1.3 Return

If a big enough free block is found, the function returns a void pointer to the RAM location of the heap memory reserved for use. A NULL pointer is returned if there isn't enough memory to allocate. Any non-NULL pointer returned must be freed for re-use by invoking `osal_mem_free()`.

14.2.2 osal_mem_free()

The `osal_mem_free()` function is a request to the memory manager to release a previously reserved block of the heap so that the memory can be re-used.

14.2.2.1 Prototype

```
void osal_mem_free( void *ptr );
```

14.2.2.2 Parameters

`ptr` – a pointer to the buffer to release for re-use – this pointer must be the non-NULL pointer that was returned by a previous call to osal_mem_alloc().

14.2.2.3 Return

None.

14.3 Strategy

Memory management should strive to maintain contiguous free space in the heap, in as few blocks as possible, with each block as big as possible. Such a general strategy helps to ensure that requests for large memory blocks always succeed if the total heap size has been set properly for the application's use pattern.

The following specific strategies have been implemented:

- Memory allocation is not penalized by having to traverse long-lived heap allocations if the system initialization is implemented as recommended within this guide.
- Memory allocation for small-blocks almost always begins searching at the first free block in the heap.
- Memory allocation attempts to coalesce all contiguous free blocks traversed in an attempt to form a single free block large enough for an allocation request.
- Memory allocation uses the first free block encountered (or created by coalescing) that is big enough to meet the request; the memory block is split if it is usefully bigger than the requested allocation.

14.4 Discussion

It is immediately after system task initialization that the effective "start of the heap" mark is set to be the first free block. Since the memory manager always starts a "walk", looking for a large enough free block, from the aforementioned mark, it will **greatly** reduce the run-time overhead of the walk if all long-lived heap allocations are packed at the start of the heap so that they will not have to be traversed on every memory allocation. Therefore, any application should make all long-lived dynamic memory allocations in its respective system initialization routine (e.g. `XXX_Init()`, where `XXX` is the Application Name). Within said system initialization routines, the long-lived items must be allocated before any short-lived items. Any short-lived items allocated must be freed before returning, otherwise the long-lived bucket may be fragmented and the run-time throughput adversely affected proportionally to the number of long-lived items that the OSAL_Memory module is forced to iterate over *for every allocation* for the rest of the life of the system. As an example, if the system initialization function starts an OSAL Timer (`osal_start_timerEx()`), this may fragment the long-lived bucket because the memory allocated for the timer will be freed and re-used throughout the life of the system (even if coincidence happens that every free and re-use is simply for resetting the same timer.) The recommended solution in this case would be to set the event corresponding to the timer (`osal_set_event ()`) and then continue to restart the timer as appropriate in the application's event handle for the corresponding event (refer to the behavior of the hal_key polling timer and corresponding event, `HAL_KEY_EVENT`). On the other hand, a reload timer (`osal_start_reload_timer()`) is a long-lived allocation and is recommended to be started during system initialization of all other long-lived items.

The application implementer must ensure that their use of dynamic memory does not adversely affect the operation of the underlying layers of the Z-Stack. The Z-Stack is tested and qualified with sample applications that make minimal use of heap memory. Thus, the user application that uses significantly more heap than the sample applications, or the user application that is built with a smaller value set for `MAXMEMHEAP` than is set in the sample applications, may inadvertently starve the lower layers of the Z-Stack to the point that they cannot function effectively or at all. For example, an application could allocate so much dynamic memory that the underlying layers of the stack would be unable to allocate enough memory to send and/or receive any OTA messages – the device would not be seen to be participating OTA.

14.5 Configuration

14.5.1 MAXMEMHEAP

The `MAXMEMHEAP` constant is usually defined in `OnBoard.h`. It must be defined to be less than **32768**.

`MAXMEMHEAP` is the number of bytes of RAM that the memory manager will reserve for the heap – it cannot be changed dynamically at runtime – it must be defined at compile-time. If `MAXMEMHEAP` is defined to be greater than or equal to `32768`, a compiler error in `OSAL_Memory.c` will trigger. `MAXMEMHEAP` does not reflect the total amount of dynamic memory that the user can expect to be usable because of the overhead cost per memory allocation.

14.5.2 OSALMEM_PROFILER

The `OSALMEM_PROFILER` constant is defined locally in `OSAL_Memory.c` to be `FALSE` by default.

After the implementation of a user application is mature, the OSAL memory manager may need to be re-tuned in order to achieve optimal run-time performance with regard to the `MAXMEMHEAP` and `OSALMEM_SMALL_BLKSZ` constants defined. The code enabled by defining the `OSALMEM_PROFILER` constant to `TRUE` allows the user to gather the empirical, run-time results required to tune the memory manager for the application. The profiling code does the following.

14.5.2.1 OSALMEM_INIT

The `OSALMEM_INIT` constant is defined locally in `OSAL_Memory.c` to be ascii '**X**'.

The memory manager initialization sets all of the bytes in the heap to the value of `OSALMEM_INIT`.

14.5.2.2 OSALMEM_ALOC

The `OSALMEM_ALOC` constant is defined locally in `OSAL_Memory.c` to be ascii '**A**'.

The user available bytes of any block allocated are set to the value of `OSALMEM_ALOC`.

14.5.2.3 OSALMEM_REIN

The `OSALMEM_REIN` constant is defined locally in `OSAL_Memory.c` to be ascii '**F**'.

Whenever a block is freed, what had been the user available bytes are set to the value of `OSALMEM_REIN`.

14.5.2.4 OSALMEM_PROMAX

The `OSALMEM_PROMAX` constant is defined locally in `OSAL_Memory.c` to be **8**.

`OSALMEM_PROMAX` is the number of different bucket sizes to profile. The bucket sizes are defined by an array:

```
  static uint16 proCnt[OSALMEM_PROMAX] = { OSALMEM_SMALL_BLKSZ,
                                         48, 112, 176, 192, 224, 256, 65535 };
```

The bucket sizes profiled should be set according to the application being tuned, but the last bucket must always be 65535 as a catch-all. There are 3 metrics kept for each bucket.

- `proCur` – the current number of allocated blocks that fit in the corresponding bucket size.

- `proMax` – the maximum number of allocated blocks that corresponded to the bucket size at once.
- `proTot` – the total number of times that a block was allocated that corresponded to the bucket size.

In addition, there is a count kept of the total number of times that the part of heap reserved for "small blocks" was too full to allow a requested small-block allocation: `proSmallBlkMiss`.

14.5.3 OSALMEM_MIN_BLKSZ

The `OSALMEM_MIN_BLKSZ` constant is defined locally in `OSAL_Memory.c`.

`OSALMEM_MIN_BLKSZ` is the minimum size in bytes of a block that is created by splitting a free block into two new blocks. The 1st new block is the size that is being requested in a memory allocation and it will be marked as in use. The 2nd block is whatever size is leftover and it will be marked as free. A larger number may result in significantly faster overall runtime of an application without necessitating any more or not very much more overall heap size. For example, if an application made a very large number of inter-mixed, short-lived memory allocations of 2 & 4 bytes each, the corresponding blocks would be 4 & 6 bytes each with overhead. The memory manager could spend a lot of time thrashing, as it were, repeatedly splitting and coalescing the same general area of the heap in order to accommodate the inter-mixed size requests.

14.5.4 OSALMEM_SMALL_BLKSZ

The `OSALMEM_SMALL_BLKSZ` constant is defined locally in `OSAL_Memory.c`.

The heap memory use of the Z-Stack was profiled using the GenericApp Sample Application and it was empirically determined that the best worst-case average combined time for a memory allocation and free, during a heavy OTA load, can be achieved by splitting the free heap into two sections. The first section is reserved for allocations of smaller-sized blocks and the second section is used for larger-sized allocations as well as for smaller-sized allocations if and when the first section is full. `OSALMEM_SMALL_BLKSZ` is the maximum block size in bytes that can be allocated from the first section.

14.5.5 OSALMEM_SMALLBLK_BUCKET

The `OSALMEM_SMALLBLK_BUCKET` constant is locally defined in `OSAL_Memory.c`.

`OSALMEM_SMALLBLK_BUCKET` is the number of bytes dedicated to the previously described first section of the heap which is reserved for smaller-sized blocks.

14.5.6 OSALMEM_NODEBUG

The `OSALMEM_NODEBUG` constant is locally defined in `OSAL_Memory.c` to be `TRUE` by default.

The Z-Stack and Sample Applications do not misuse the heap memory API. The onus to be equally correct is on the user application: in order to provide the minimum throughput latency possible, there are no run-time checks for correct use of the API. An application can be shown to be correct by defining the `OSALMEM_NODEBUG` constant to `FALSE`. Such a setting will enable code that traps on the following misuse scenario.

- Invoking `osal_mem_alloc()` with size equal to zero.

Warning: invoking `osal_mem_free()` with a dangling or invalid pointer cannot be detected.

14.5.7 OSALMEM_PROFILER_LL

The `OSALMEM_PROFILER_LL` constant is defined locally in `OSAL_Memory.c` to be `FALSE` by default.

Normally, the allocations that are packed into the Long-Lived bucket by all of the system initialization should not be counted during "profiling" because they are not iterated over during run-time. But, in order to properly tune the size of the Long-Lived bucket for any given Application, this constant should be used for one run on the debugger with a mature implementation. The numbers used in the following example are for the 8051 SOC, GenericApp, with out-of-the-box settings and thus using this default:

```
#define OSALMEM_LL_BLKSZ          (OSALMEM_ROUND(417) + (19 * OSALMEM_HDRSZ))
```

1. Define `OSALMEM_PROFILER` and `OSALMEM_PROFILER_LL` to `TRUE`

2. Set a break point in `osal_mem_kick()` after this operation:

    a. ff1 = tmp – 1;

3. Inspect the variable `proCur` in an IAR 'Watch' window and sum the counts of all of the buckets (19 in this example) and plug it into the formula above – this is the count of long-lived items.

4. Subtract the value of ff1 (0x1095 in one particular run) from the location of theHeap (0x0ECE in that same run) and then subtract the sub-total of the count of long-lived items multiplied by the `OSALMEM_HDRSZ` (19 * 2 = 38 for this example.)

Further memory profiling should now be done with `OSALMEM_PROFILER_LL` set back to `FALSE` so as not to count the long-lived allocations in the statistics.

15. Compile Options

15.1 Overview

This section provides information and procedures for using compiler options with Texas Instruments Z-Stack™, and it's recommend that you don't change compile flags that aren't listed in this section.

15.2 Requirements

15.2.1 Target Development System Requirements

Z-Stack is built on top of the IAR Embedded Workbench suite of software development tools (www.iar.com). These tools support project management, compiling, assembling, linking, downloading, and debugging for various development platforms. The following are required support for the Z-Stack target development system:

Platform/Target	Compiler/Tool
EXP5438 + CC2520	IAR EW430
SmartRF05EB + CC2530	IAR EW8051
SmartRF06EB + CC2538	IAR EWARM

15.3 Using Z-Stack Compile Options

15.3.1 Selecting the Logical Device Type

ZigBee devices can be configured in one of three ways (each of these device types are explained in the Z-Stack Developer's Guide), and your application will be hosted on one (or more) of these device types:

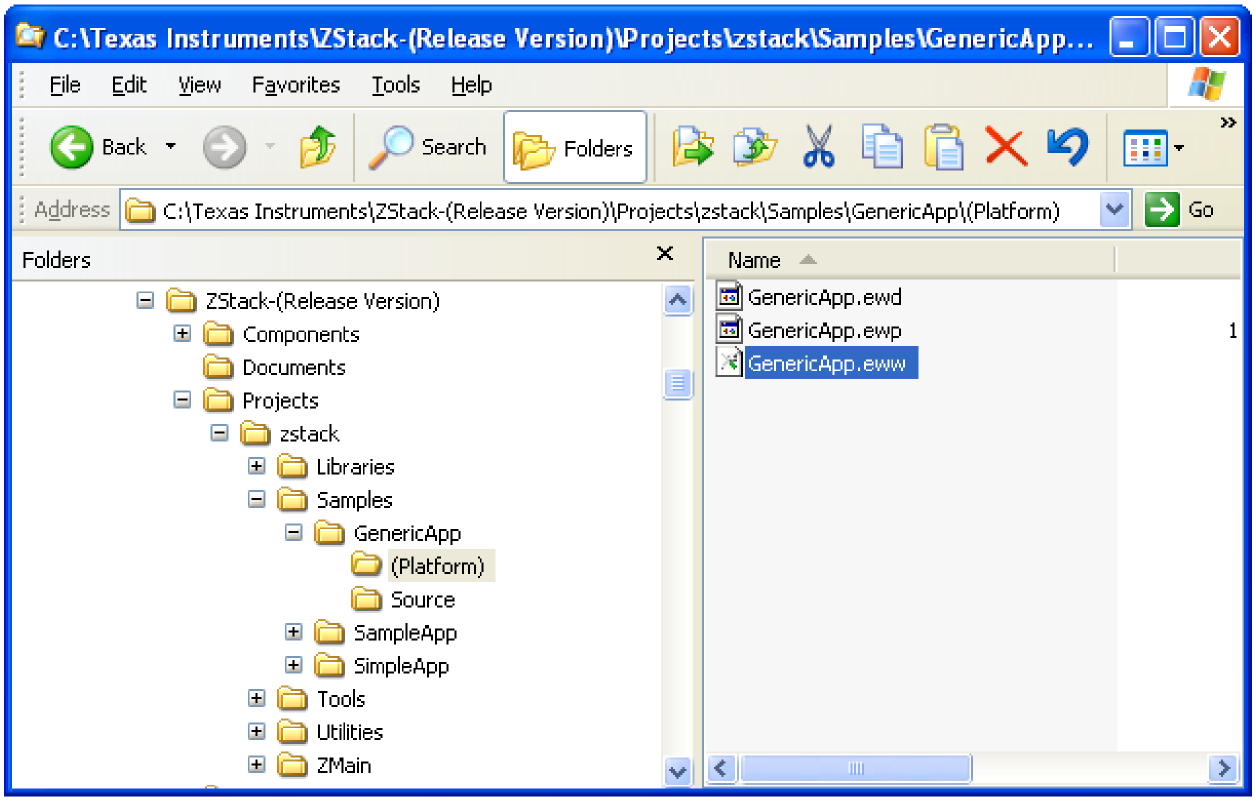
- ZigBee Coordinator – This device is configured to start the IEEE 802.15.4 network and will serve as the PAN Coordinator in that network.
- ZigBee Router – This device is configured to associate with a ZigBee Coordinator, then allow other routers or end devices to associate with it. It will route data packets in the network.
- ZigBee End Device – This device is configured to join a pre-existing network and will associate with a ZigBee Coordinator or ZigBee Router.

15.3.2 Locating Compile Options

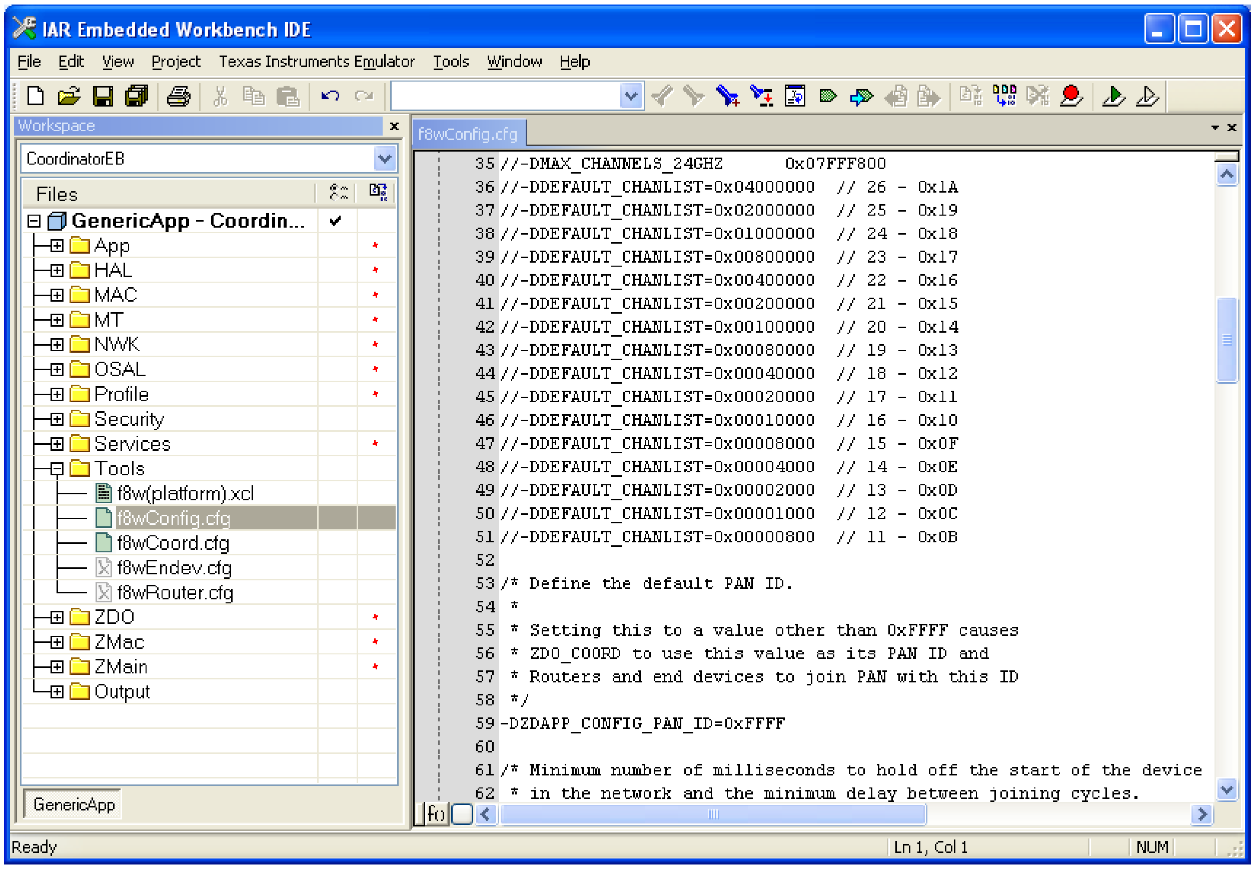
Compile options for a specific project are located in two places. Options that are rarely, if ever, changed are located in linker control files, one for each logical device type discussed above. User-defined options and ones that change to enable/disable features are located in the IAR project file. For demonstration purposes, these two files for the GenericApp Coordinator project will be examined. Access to all other Z-Stack projects will be similar.

15.3.2.1 Compile Options In Linker Control Files

GenericApp project files are found in the **..\Projects\zstack\Samples\GenericApp\(Platform)** folder:

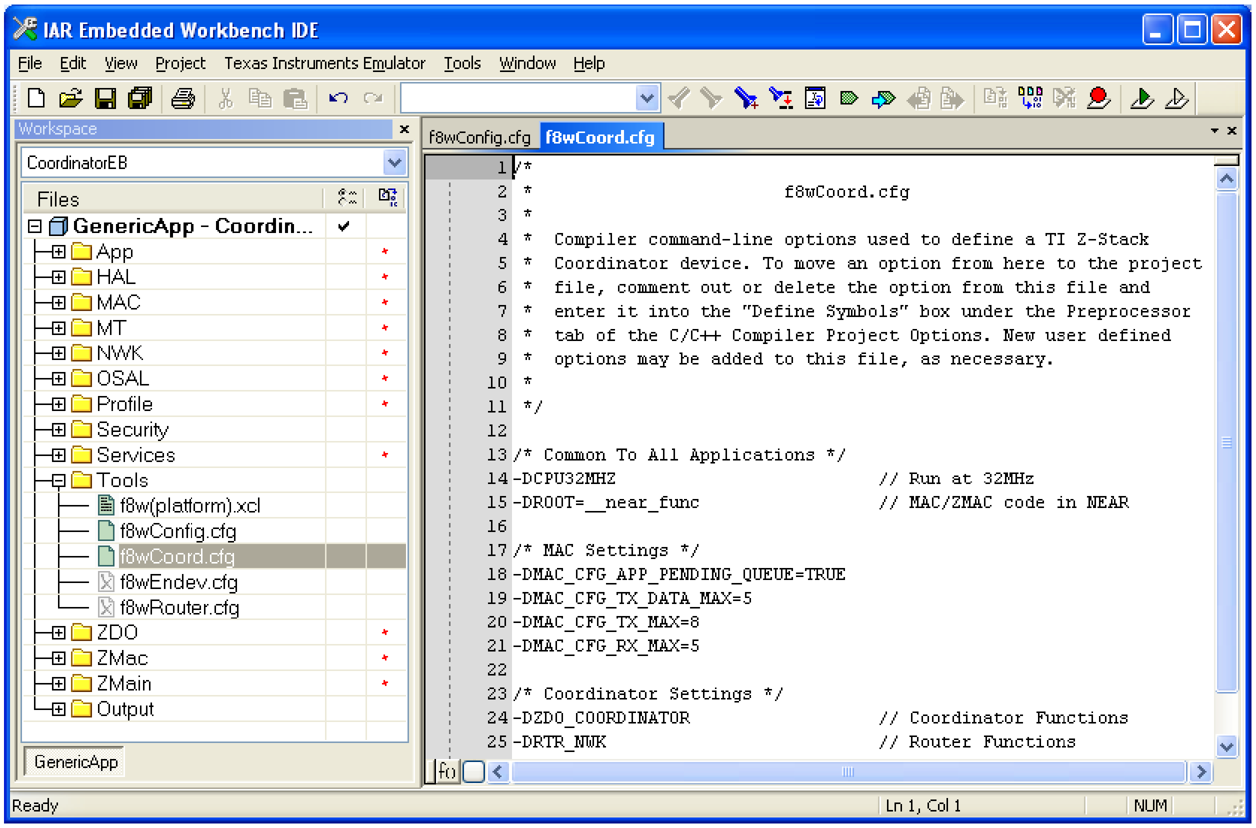


Open the project by double-clicking on the *GenericApp.eww* file, select the *CoordinatorEB* configuration from the pull-down list below **Workspace**, and then open the **Tools** folder. Several linker control files are located in the **Tools** folder. This folder contains various configuration files and executable tools used in Z-Stack projects. Generic compile options are defined in the `f8wConfig.cfg` file. This file, for example, specifies the channel(s) and the PAN ID that will be used when a device starts up. This is the recommended location for a user to establish specific channel settings for their projects. This allows developers set up "personal" channels to avoid conflict with others. Device specific compile options are located in the `f8wCoord.cfg`, `f8wEndev.cfg`, and `f8wRouter.cfg` files:



```
//-DMAX_CHANNELS_24GHZ       0x07FFF800
//-DDEFAULT_CHANLIST=0x04000000  // 26 - 0x1A
//-DDEFAULT_CHANLIST=0x02000000  // 25 - 0x19
//-DDEFAULT_CHANLIST=0x01000000  // 24 - 0x18
//-DDEFAULT_CHANLIST=0x00800000  // 23 - 0x17
//-DDEFAULT_CHANLIST=0x00400000  // 22 - 0x16
//-DDEFAULT_CHANLIST=0x00200000  // 21 - 0x15
//-DDEFAULT_CHANLIST=0x00100000  // 20 - 0x14
//-DDEFAULT_CHANLIST=0x00080000  // 19 - 0x13
//-DDEFAULT_CHANLIST=0x00040000  // 18 - 0x12
//-DDEFAULT_CHANLIST=0x00020000  // 17 - 0x11
//-DDEFAULT_CHANLIST=0x00010000  // 16 - 0x10
//-DDEFAULT_CHANLIST=0x00008000  // 15 - 0x0F
//-DDEFAULT_CHANLIST=0x00004000  // 14 - 0x0E
//-DDEFAULT_CHANLIST=0x00002000  // 13 - 0x0D
//-DDEFAULT_CHANLIST=0x00001000  // 12 - 0x0C
//-DDEFAULT_CHANLIST=0x00000800  // 11 - 0x0B

/* Define the default PAN ID.
 *
 * Setting this to a value other than 0xFFFF causes
 * ZDO_COORD to use this value as its PAN ID and
 * Routers and end devices to join PAN with this ID
 */
-DZDAPP_CONFIG_PAN_ID=0xFFFF

/* Minimum number of milliseconds to hold off the start of the device
 * in the network and the minimum delay between joining cycles.
```

The GenericApp Coordinator project uses the `f8wCoord.cfg` file. As shown below, compile options that are specific to Coordinator devices and options that provide "generic" Z-Stack functions are included in this file:



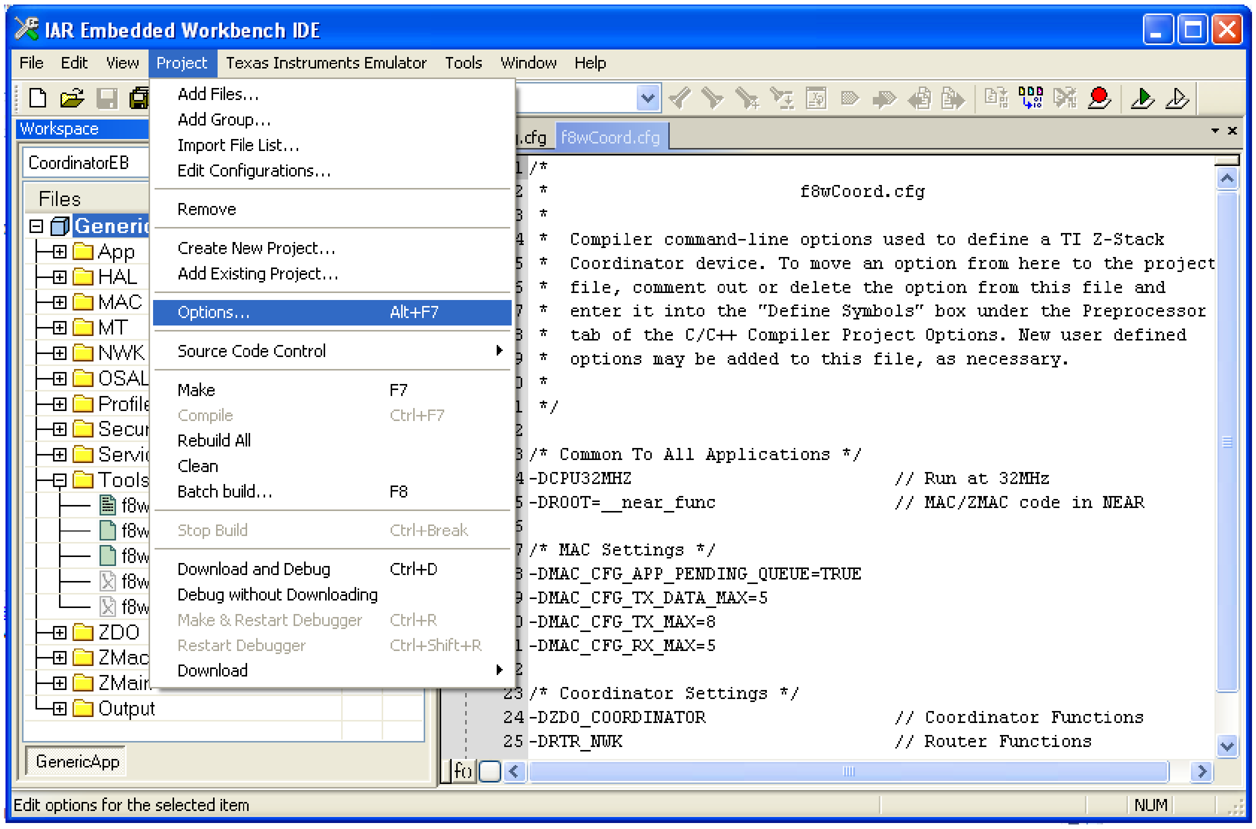
```
/*
 *                              f8wCoord.cfg
 *
 *   Compiler command-line options used to define a TI Z-Stack
 *   Coordinator device. To move an option from here to the project
 *   file, comment out or delete the option from this file and
 *   enter it into the "Define Symbols" box under the Preprocessor
 *   tab of the C/C++ Compiler Project Options. New user defined
 *   options may be added to this file, as necessary.
 *
 */

/* Common To All Applications */
-DCPU32MHZ                              // Run at 32MHz
-DROOT=__near_func                      // MAC/ZMAC code in NEAR

/* MAC Settings */
-DMAC_CFG_APP_PENDING_QUEUE=TRUE
-DMAC_CFG_TX_DATA_MAX=5
-DMAC_CFG_TX_MAX=8
-DMAC_CFG_RX_MAX=5

/* Coordinator Settings */
-DZDO_COORDINATOR                       // Coordinator Functions
-DRTR_NWK                               // Router Functions
```

The `f8wCoord.cfg` file is used by all projects that build Coordinator devices. Therefore, any change made to this file will affect all Coordinators. In a similar manner, the `f8wRouter.cfg` and `f8wEnd.cfg` files affect all Router and End-Device projects, respectively.

To add a compile option to all projects of a certain device type, simply add a new line to the appropriate linker control file. To disable a compile option, comment that option out by placing // at the left edge of the line. You could also delete the line but this is not recommended since the option might need to be re-enabled at a later time.

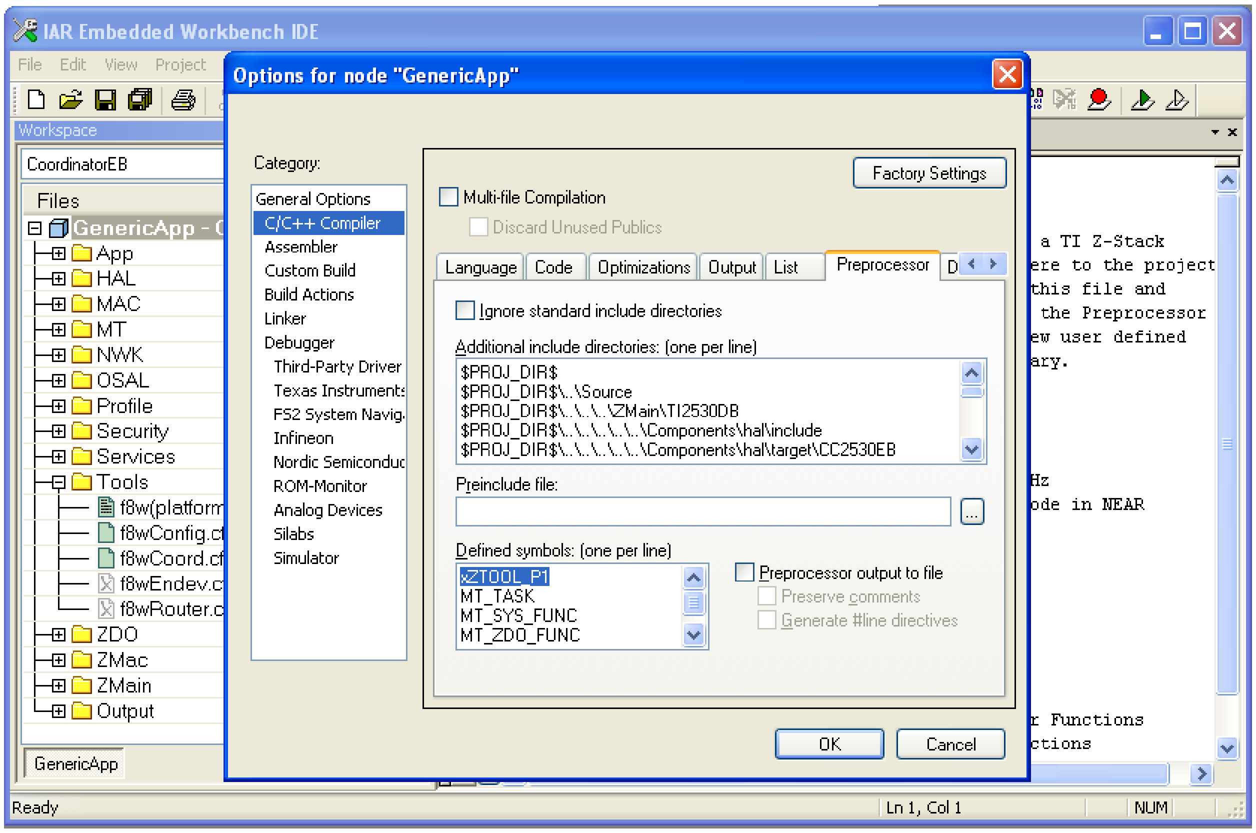
15.3.2.2 Compile Options In IAR Project Files

The compile options for each of the supported configurations are stored in the *GenericApp.ewp* file. To modify these compile options, first select **GenericApp – CoordinatorEB**. Then select the **Options…** item from the **Project** pull-down menu:



```
/*
 *                             f8wCoord.cfg
 *
 *  Compiler command-line options used to define a TI Z-Stack
 *  Coordinator device. To move an option from here to the project
 *  file, comment out or delete the option from this file and
 *  enter it into the "Define Symbols" box under the Preprocessor
 *  tab of the C/C++ Compiler Project Options. New user defined
 *  options may be added to this file, as necessary.
 *
 */

/* Common To All Applications */
-DCPU32MHZ                                 // Run at 32MHz
-DROOT=__near_func                         // MAC/ZMAC code in NEAR

/* MAC Settings */
-DMAC_CFG_APP_PENDING_QUEUE=TRUE
-DMAC_CFG_TX_DATA_MAX=5
-DMAC_CFG_TX_MAX=8
-DMAC_CFG_RX_MAX=5

/* Coordinator Settings */
-DZDO_COORDINATOR                          // Coordinator Functions
-DRTR_NWK                                  // Router Functions
```

Select the **C/C++ Compiler** item and click on the **Preprocessor** tab. The compile options for this configuration are located in the box labeled *Defined symbols: (one per line)*:



Options for node "GenericApp"

Category:

- General Options
- C/C++ Compiler
- Assembler
- Custom Build
- Build Actions
- Linker
- Debugger
- Third-Party Driver
- Texas Instruments
- FS2 System Navig.
- Infineon
- Nordic Semiconduc
- ROM-Monitor
- Analog Devices
- Silabs
- Simulator

Factory Settings

[ ] Multi-file Compilation

[ ] Discard Unused Publics

Language | Code | Optimizations | Output | List | Preprocessor | D

[ ] Ignore standard include directories

Additional include directories: (one per line)

```
$PROJ_DIR$
$PROJ_DIR$\..\Source
$PROJ_DIR$\..\..\..\ZMain\TI2530DB
$PROJ_DIR$\..\..\..\..\Components\hal\include
$PROJ_DIR$\..\..\..\..\Components\hal\target\CC2530EB
```

Preinclude file:

Defined symbols: (one per line)

```
xZTOOL_P1
MT_TASK
MT_SYS_FUNC
MT_ZDO_FUNC
```

[ ] Preprocessor output to file

[ ] Preserve comments

[ ] Generate #line directives

OK Cancel

```
a TI Z-Stack
ere to the project
this file and
 the Preprocessor
ew user defined
ary.

Hz
ode in NEAR

r Functions
ctions
```

To add a compile option to this configuration, simply add the item on a new line within this box. To disable a compile option, place an '**x**' at the left edge of the line. Note that the **ZTOOL_P1** option has been disabled in the example shown above. This option could have been deleted but this is not recommended since it might need to be re-enabled at a later time.

15.3.3 Using Compile Options

Compile options are used to select features that are provided in the source files. Most compile options act as on/off switches for specific sections within source programs. Some options are used to provide a user-defined numerical value, such as `DEFAULT_CHANLIST`, to the compiler to override default values.

Each of the Z-Stack sample applications (ex. GenericApp) provide an IAR project file which specifies the compile options to be used for that specific project. The programmer can add or remove options as needed to include or exclude portions of the available software functions. Note that changing compile options may require other changes to the project file (see 15.3.2). For example, adding the `MT_NWK_FUNC` option requires `MT_NWK.c` to be in the list of source files in the configuration of the device you are building.

The next sections of this document provide lists of the supported compile options with a brief description of what feature they enable or disable. Options that are listed as "do not change" are required for proper operation of the compiled programs. Options that are listed as "*do not use*" are not appropriate for use with the board.

15.4 Supported Compile Options and Definitions

15.4.1 General Compile Options

The compile options in the following table can be changed or set to select desired features, a lot of these compile options are set and described in `f8wConfig.cfg`.

APS_DEFAULT_INTERFRAME_DELAY	Delay between Tx packets when using fragmentation
APS_DEFAULT_MAXBINDING_TIME	Maximum time in seconds that a Coordinator will wait between receiving match descriptor bind requests to perform binding
APS_DEFAULT_WINDOW_SIZE	Size of a Tx window when using fragmentation
APS_MAX_GROUPS	Maximum number of entries allowed in the groups table
APSC_ACK_WAIT_DURATION_POLLED	Number of 2 milliseconds periods a polling End Device will wait for an APS acknowledgement from the destination device
APSC_MAX_FRAME_RETRIES	Maximum number of retries allowed (at APS layer) after a transmission failure
ASSERT_RESET	Specifies that the device should reset when there's an assertion. When not defined, all LEDs will flash when an assertion occurs.
BEACON_REQUEST_DELAY	Minimum number of milliseconds to delay between each beacon request in a joining cycle
BLINK_LEDS	Enable extended LED blinking functions
DEFAULT_CHANLIST	Change this list in f8wConfig.cfg
EXTENDED_JOINING_RANDOM_MASK	Mask for the random joining delay
HOLD_AUTO_START	Disable automatic start-up of ZDApp event processing loop
LCD_SUPPORTED	Enable LCD emulation – text sent to ZTool serial port
MANAGED_SCAN	Enable delays between channel scans
MAX_BCAST	Maximum number of simultaneous broadcasts supported by a device at any given time
MAX_BINDING_CLUSTER_IDS	Maximum number of cluster IDs in a binding record
MAX_POLL_FAILURE_RETRIES	Number of times retry to poll parent before indicating loss of synchronization with parent. Note that larger value will cause longer delay for the child to rejoin the network
MAX_RREQ_ENTRIES	Number of simultaneous route discoveries in network
MAX_RTG_ENTRIES	Number of entries in the regular routing table plus additional entries for route repair
MAXMEMHEAP	Determines the total memory available for dynamic memory. Every request for an amount of dynamic memory requires dynamic memory space for overhead used in managing the allocated memory. So MAXMEMHEAP does not reflect the total amount of dynamic memory that the user can expect to be usable. As a rule of thumb, each memory allocation requires at least 2+N bytes, where N represents the word-alignment block size of the target CPU (e.g., N=1 on the AVR and CC2430 but N=2 on the MSP430). MAXMEMHEAP must be defined to be less that 32768
NONWK	Disable NWK, APS, and ZDO functionality
NV_INIT	Enable loading of "basic" NV items at device reset
NV_RESTORE	Enables device to save/restore network state information to/from NV
NWK_AUTO_POLL	Enable End Device to poll from the parents automatically
NWK_INDIRECT_MSG_TIMEOUT	Number of milliseconds the parent of a polling End Device will hold a message
NWK_MAX_BINDING_ENTRIES	Maximum number of entries in the binding table
NWK_MAX_DATA_RETRIES	The maximum number of times retry looking for the next hop address of a message
NWK_MAX_DEVICE_LIST	Maximum number of devices in the Association/Device list

NWK_MAX_DEVICES	Maximum number of devices in the network
NWK_START_DELAY	Minimum number of milliseconds to hold off the start of the device in the network and the minimum delay between joining cycles
OSAL_TOTAL_MEM	Track OSAL memory heap usage (display if LCD_SUPPORTED)
POLL_RATE	For end devices only: number of milliseconds to wait between data request polls to its parent. Example POLL_RATE=1000 is a data request every second. This is changed in *f8wConfig.cfg*.
POWER_SAVING	Enable power saving functions for battery-powered devices
QUEUED_POLL_RATE	This is used after receiving a data indication to poll immediately for queued messages (in milliseconds)
REFLECTOR	Enable binding
REJOIN_POLL_RATE	This is used as an alternate response poll rate only for rejoin request. This rate is determined by the response time of the parent that the device is trying to join
RESPONSE_POLL_RATE	This is used after receiving a data confirmation to poll immediately for response messages (in milliseconds)
ROUTE_EXPIRY_TIME	Number of seconds before an entry expires in the routing table; set to 0 to turn off route expiry
RTR_NWK	Enable Router networking
SECURE	Enable ZigBee security (SECURE=0 to disable, SECURE=1 to enable)
ZAPP_Px	Enable ZApp messages via serial port Px where x is the port (1 or 2)
ZDAPP_CONFIG_PAN_ID	Coordinator's PAN ID; used by Routers and End Devices to join PAN with this ID
ZDO_COORDINATOR	Enable the device as a Coordinator
ZIGBEEPRO	Enable usage of ZigBee Pro features
ZTOOL_Px	Enable ZTool messages via serial port Px where x is the port (1 or 2)
OSC32K_CRYSTAL_INSTALLED	This compilation flag defines whether to use the internal 32 Khz RC OSC (if set to false) or an external 32 Khz crystal when mounted on board**.** **Important note: If this compilation flag is not defined, the SW select the 32 Khz external OSC configuration by default** (as 253x EM have an external 32 Khz populated). If your design doesn't have an external 32 Khz on board, please make sure you set **OSC32K_CRYSTAL_INSTALLED = FALSE** in your compiler project settings.

15.4.2 Non-changeable Compile Options

These compile options in the following table should not be changed or used. Not all of them are available in every platform:

CPU32MHZ	Clock rate of the CPU – 32 MHZ **(do not change)**
MACSIM	Enable MAC simulation **(do not use)**
NWK_TEST	Enable Network test functions **(do not use)**

15.4.3 Monitor-Test (MT) Compile Options

Please read the Z-Stack Monitor and Test API document before changing any of these compile options. You can enable the following APIs and function associated with the `MT_TASK` option, but you must include the `MT_TASK` option.

MT_TASK	Enable Monitor-Test task
MT_AF_FUNC	Enable Monitor-Test processing of AF commands issued from ZTool or ZTrace
MT_AF_CB_FUNC	Enable Monitor-Test processing of AF callbacks registered by ZTool or ZTrace
MT_APP_FUNC	Enable Monitor-Test processing of APP commands issued from ZTool or ZTrace
MT_DEBUG_FUNC	Enable Monitor-Test processing of DEBUG commands issued from ZTool or ZTrace
MT_MAC_FUNC	Enable Monitor-Test processing of MAC commands issued from ZTool or ZTrace
MT_NWK_FUNC	Enable Monitor-Test processing of NWK commands issued from ZTool or ZTrace
MT_NWK_CB_FUNC	Enable Monitor-Test processing of NWK callbacks registered by ZTool or ZTrace
MT_SAPI_FUNC	Enable Monitor-Test processing of SAPI commands issued from ZTool or ZTrace
MT_SAPI_CB_FUNC	Enable Monitor-Test processing of SAPI callbacks registered by ZTool or ZTrace
MT_SYS_FUNC	Enable Monitor-Test processing of SYS commands issued from ZTool or ZTrace

MT_SYS_OSAL_NV_READ_CERTIFICATE_DATA	Default define to FALSE in MT_SYS.c and only applicable if ZCL_KEY_ESTABLISH is defined. If ZCL_KEY_ESTABLISH is defined and MT_SYS_OSAL_NV_READ_CERTIFICATE_DATA is defined to TRUE, then the three NV items containing Certicom certificate data can be read via MT:
	`ZCD_NV_IMPLICIT_CERTIFICATE 0x0069`
	`ZCD_NV_DEVICE_PRIVATE_KEY 0x006A`
	`ZCD_NV_CA_PUBLIC_KEY 0x006B`
	Otherwise, the certificate data cannot be read via MT.

MT_UTIL_FUNC	Enable Monitor-Test processing of UTIL commands issued from ZTool or ZTrace
MT_ZDO_CB_FUNC	Enable Monitor-Test processing of ZDO commands issued from ZTool or ZTrace
MT_ZDO_FUNC	Enable Monitor-Test processing of ZDO commands issued from ZTool or ZTrace
MT_ZDO_MGMT	Enable Monitor-Test processing of ZDO MGMT commands from ZTool or ZTrace

15.4.4 ZigBee Device Object (ZDO) Compile Options

By default, the mandatory messages (as defined by the ZigBee spec) are enabled in the ZDO. All other message processing is controlled by compile flags. You can enable/disable the options by commenting/un-commenting the compile flags in `ZDConfig.h` or include/exclude them like other compile flags. There's an easy way to enable all the ZDO Function and Management options: You can use `MT_ZDO_FUNC` to enable all the ZDO Function options, and `MT_ZDO_FUNC` and `MT_ZDO_MGMT` to enable all the ZDO Function plus Management options. Information about the use of these messages is provided in this guide and Z-Stack API document.

ZDO_NWKADDR_REQUEST	Enable Network Address Request function and response processing
ZDO_IEEEADDR_REQUEST	Enable IEEE Address Request function and response processing
ZDO_MATCH_REQUEST	Enable Match Descriptor Request function and response processing
ZDO_NODEDESC_REQUEST	Enable Node Descriptor Request function and response processing
ZDO_POWERDESC_REQUEST	Enable Power Descriptor Request function and response processing
ZDO_SIMPLEDESC_REQUEST	Enable Simple Descriptor Request function and response processing
ZDO_ACTIVEEP_REQUEST	Enable Active Endpoint Request function and response processing
ZDO_COMPLEXDESC_REQUEST	Enable Complex Descriptor Request function and response processing
ZDO_USERDESC_REQUEST	Enable User Descriptor Request function and response processing
ZDO_USERDESCSET_REQUEST	Enable User Descriptor Set Request function and response processing
ZDO_ENDDEVICEBIND_REQUEST	Enable End Device Bind Request function and response processing
ZDO_BIND_UNBIND_REQUEST	Enable Bind and Unbind Request function and response processing
ZDO_SERVERDISC_REQUEST	Enable Server Discovery Request function and response processing
ZDO_MGMT_NWKDISC_REQUEST	Enable Mgmt Nwk Discovery Request function and response processing
ZDO_MGMT_LQI_REQUEST	Enable Mgmt LQI Request function and response processing
ZDO_MGMT_RTG_REQUEST	Enable Mgmt Routing Table Request function and response processing
ZDO_MGMT_BIND_REQUEST	Enable Mgmt Binding Table Request function and response processing
ZDO_MGMT_LEAVE_REQUEST	Enable Mgmt Leave Request function and response processing
ZDO_MGMT_JOINDIRECT_REQUEST	Enable Mgmt Join Direct Request function and response processing
ZDO_MGMT_PERMIT_JOIN_REQUEST	Enable device to respond to Mgmt Permit Join Request function
ZDO_USERDESC_RESPONSE	Enable device to respond to User Descriptor Request function
ZDO_USERDESCSET_RESPONSE	Enable device to respond to User Descriptor Set Request function
ZDO_SERVERDISC_RESPONSE	Enable device to respond to Server Discovery Request function
ZDO_MGMT_NWKDISC_RESPONSE	Enable device to respond to Mgmt Network Discovery Request function
ZDO_MGMT_LQI_RESPONSE	Enable device to respond to Mgmt LQI Request function
ZDO_MGMT_RTG_RESPONSE	Enable device to respond to Mgmt Routing Table Request function
ZDO_MGMT_BIND_RESPONSE	Enable device to respond to Mgmt Binding Table Request function
ZDO_MGMT_LEAVE_RESPONSE	Enable device to respond to Mgmt Leave Request function
ZDO_MGMT_JOINDIRECT_RESPONSE	Enable device to respond to Mgmt Join Direct Request function
ZDO_MGMT_PERMIT_JOIN_RESPONSE	Enable device to respond to Mgmt Permit Join Request function
ZDO_ENDDEVICE_ANNCE	Enable device to respond to End Device Annce Message function
ZDO_NV_SAVE_RFDs	Default define to TRUE in ZDApp.c and only applicable if NV_RESTORE is defined. If NV_RESTORE is defined and ZDO_NV_SAVE_RFDs is defined to FALSE, then RFD joins will not trigger a call to NLME_UpdateNV() and the delay time between receiving a trigger event and actually invoking NLME_UpdateNV() is extended to the OSAL timer maximum of 65 seconds (see ZDAPP_UPDATE_NWK_NV_TIME). This compile option is intended to be used to greatly extend the life of the NV pages of the RFD's in a network with mobile or purged RFD's. When this flag is defined to FALSE, any RFD children that exist at the time an FFD is reset will not be restored and the FFD can re-issue their network addresses to other joining RFD's.
ZDAPP_UPDATE_NWK_NV_TIME	Default define to 700 msecs and only applicable if NV_RESTORE is defined. The delay time between receiving a network save state trigger event and actually invoking NLME_UpdateNV(). The longer this delay is, the longer the life of the NV pages since this data is very large and in a busy network (especially one with mobile RFD's) the frequency of trigger events could be high.