



Z-Stack Developer's Guide

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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 |
| CCM* | Enhanced counter with CBC-MAC mode of operation |
| EPID | Extended PAN ID |
| MSG | Message |
| NHLE | Next Higher Layer Entity |
| NIB | Network Information Base |
| NWK | Network |
| PAN | Personal Area Network |
| SE | Smart Energy |
| ZDO | ZigBee Device Object |

1.4 Reference Documents

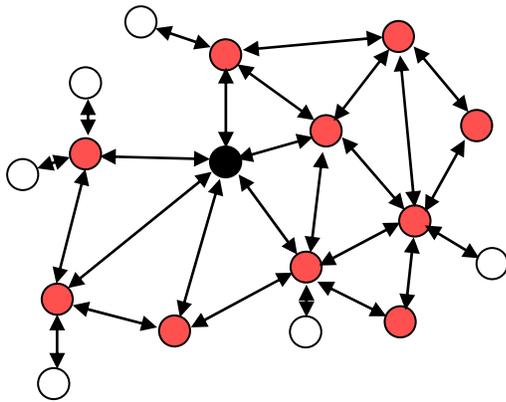
- [1] ZigBee Specification, R17, ZigBee Alliance document number 053474r17ZB.
- [2] Z-Stack API (SWRA195)

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 doc].

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 Doc):

- `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 Doc). 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.

All sample applications have a function that handles key events [for example, `TransmitApp_HandleKeys()` in `TransmitApp.c`]. The SW2 key handler calls `ZDP_EndDeviceBindReq()` [`ZDProfile.c`] to send the End Device Bind Request message to the coordinator, with only the cluster IDs relevant to the `TransmitApp` application. Or, as in `SampleLight` and `SampleSwitch`, `ZDP_EndDeviceBindReq()` is called directly with only the cluster IDs relevant to the lamp On/Off functions.

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()` -

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 your 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 (ref. Z-Stack API 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 can not 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.

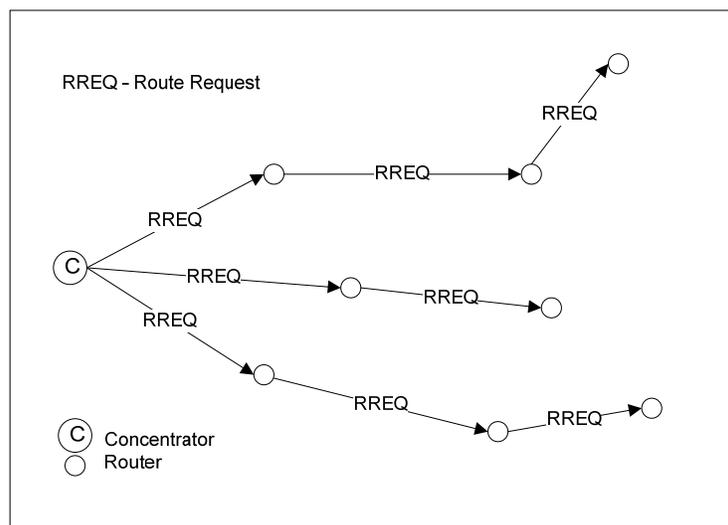


Figure 1: Many-to-one route discovery illustration

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 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.

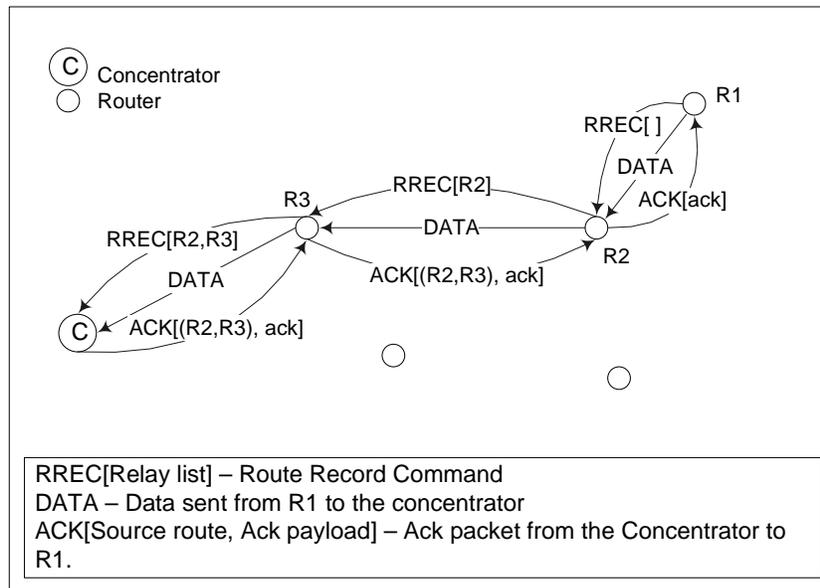


Figure 2: Route record command (source routing) illustration

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

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.

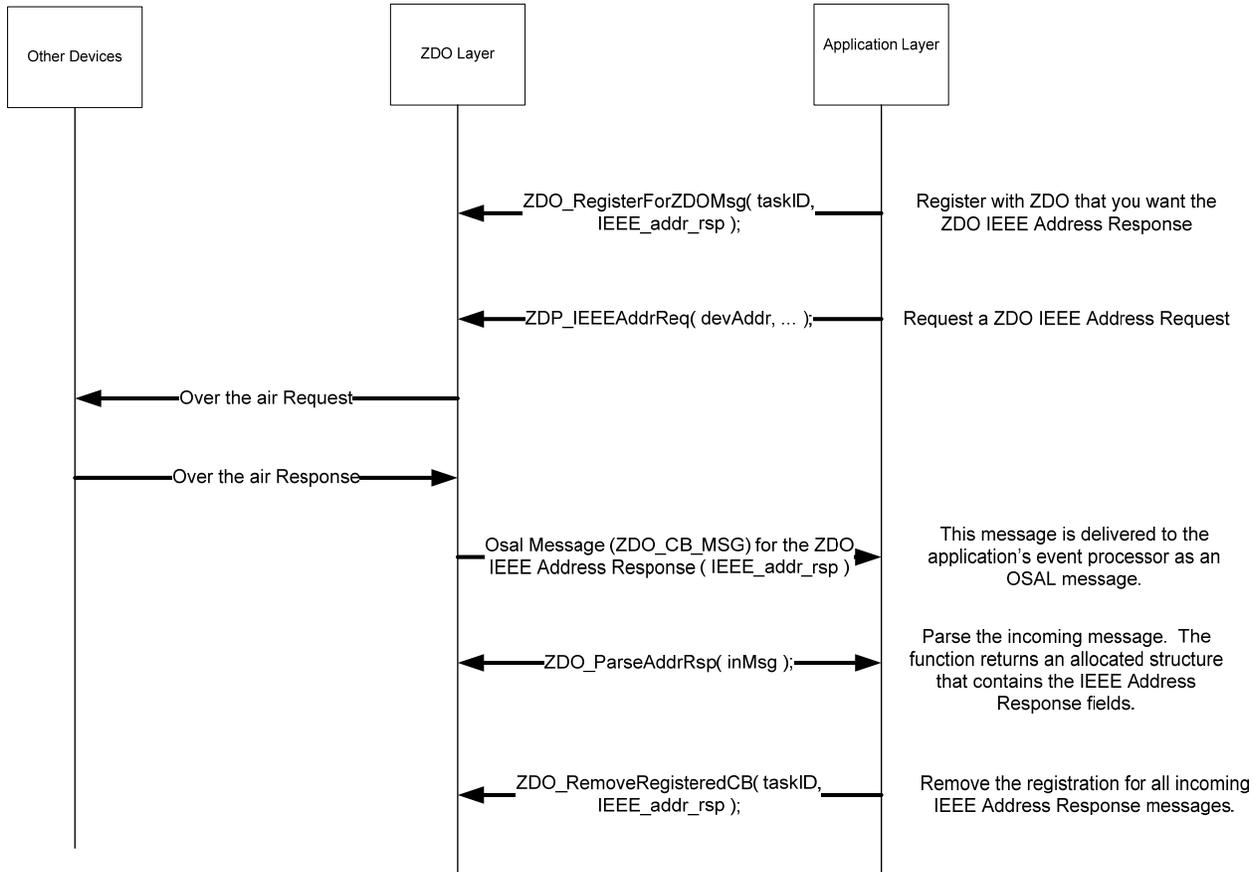


Figure 3: ZDO IEEE Address Request and Response

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_ance) messages.

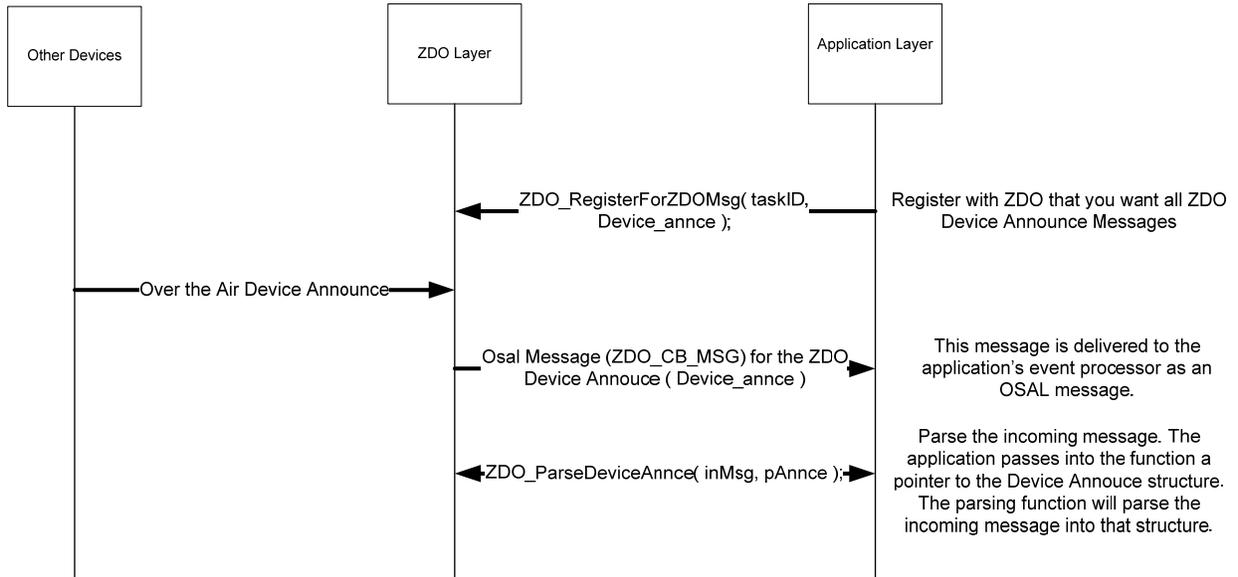


Figure 4: ZDO Device Announce delivered to an application

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 changeable 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 0xFFFFE). A coordinator will use this value as the PANId of the network that it starts. A router or end-device will only join a network that has a PANId 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 Stack API 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.

Although the “`NLME-LEAVE.request`” offers several optional parameters, ZigBee 2007 (as well as Texas Instrument’s current implementation) limits the use of these parameters. Currently, the optional parameters (“`RemoveChildren`”, “`Rejoin`”, and “`Silent`”) should be set to the default values used in “`ZDO_ProcessMgmtLeaveReq`”. If these values are changed unexpected results may occur.

9.5 Descriptors

All devices in a ZigBee network have descriptors that describe that 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 ZStack. To store and restore these items from non-volatile memory include the `NV_INIT` compile flag in your project.

9.6.2 Network Layer Non-Volatile Memory

A ZigBee device has lot 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.

When a device starts up after a reset, this information is restored into the device. 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 `ZDO_DefaultUserDescriptor()` [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 it 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. In the same applications, this compile flag will include the APS Fragmentation task [`APSF_Init()` and `APSF_ProcessEvent()`]. If you have an existing application, copy the code in the `OSAL_XXX.c` (ie. `OSAL_GenericApp.c`) sample application file – search for `ZIGBEE_FRAGMENTATION`.

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

There are a couple of fragmentation control variables that the application (or profile) can set/change (defined in ZGlobals.c):

- `zgApscMaxWindowSize` - 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. `ZCD_NV_APSF_WINDOW_SIZE` is the NV item for this variable. If one packet of the window size isn't received, the ACK is not sent and all the packets (within that window) are resent.
- `zgApsInterframeDelay` - The delay between fragments within a window. This is used by the sending device. `ZCD_NV_APSF_INTERFRAME_DELAY` is the NV item for this variable.

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 | <code>zgApscMaxWindowSize</code> (defined in <code>ZGlobals.h</code>) |
| Interframe delay | <code>zgApsInterframeDelay</code> (defined in <code>ZGlobals.h</code>) |
| Application/Profile maximum buffer size | <code>MAX_TRANSFER_SIZE</code> (defined in <code>ZDConfig.h</code>) |

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 PANID 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.

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`) 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 `zgPreConfigKeys` 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 broadcast a new Network key to all devices on the network. At this point the new Network key is stored as an alternate key in all devices. Once the Trust Center calls `ZDSecMgrSwitchNwkKey()`, a network wide broadcast will trigger all devices to use their alternate key.

10.5 Smart Energy Secure Joining

The Smart Energy Profile requires 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 Smart Energy Profile device.

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 figure. Notice that the APS Update Device command sent from the parent to the trust center is network layer encrypted. The APS Tunnel Command with APS Transport Key command as the payload is also 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.

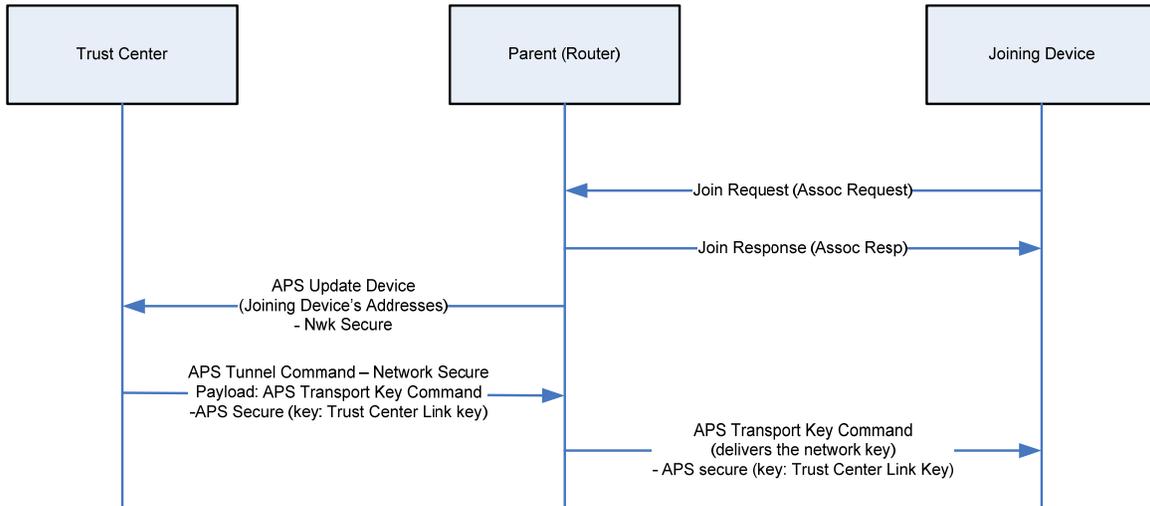


Figure 5: Smart Energy Secure Joining – Parent is not the Trust Center

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

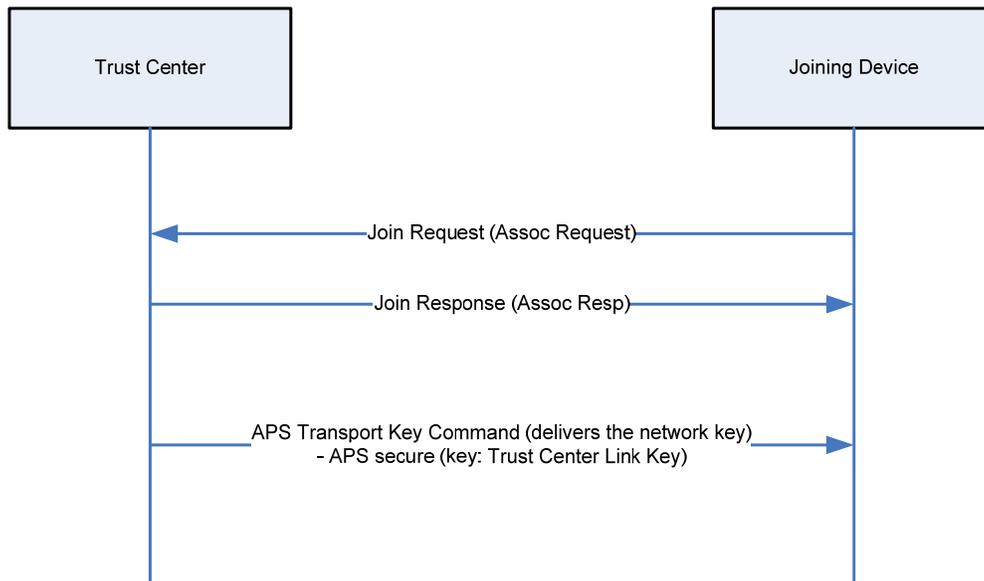


Figure 6: Smart Energy Secure Joining – Parent is the Trust Center

To enable the Smart Energy Secure Joining feature, set SECURE=1 in f8wConfig.cfg and include the SE_PROFILE compile flag. Also, there are needed compiler flags, global variables (ZGlobals) and NV Items.

There are two modes in using smart energy secure joining: Multiple Key Mode and Single Key Mode. In multiple key mode, unique pre-configured trust center link keys are used between the trust center and each individual device joining the network. Multiple key mode is required by the recommended secure procedure in ZigBee SE profile Specification. In single key mode, all devices are using the same pre-configured trust center link key to join the network. The single key mode provides a simplified alternative procedure to set up the network. It can be used for testing and debugging purpose.

To start the network using Multiple Key Mode:

- Set `zgUseDefaultTCLK=FALSE` (defined in `ZGlobals`). The NV item for this global is `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. | <code>ZCD_NV_TCLK_TABLE_START</code> 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 the multiple key mode to make sure there is no existing NV item for the preconfigured trust center link keys.

To start the network using Single Key Mode:

- Set `zgUseDefaultTCLK=TRUE` (defined in `ZGlobals`). The NV item for this global is `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`). 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 single key mode 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 Single Key Mode and Multiple Key Mode shall be used exclusively.

10.6 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 |
|---|--------|-------------------------------------|
| <code>ZCD_NV_NWK_ACTIVE_KEY_INFO</code> | 0x003A | Active Network key |
| <code>ZCD_NV_NWK_ALTERN_KEY_INFO</code> | 0x003B | Alternate Network Key |
| <code>ZCD_NV_TCLK_TABLE_START</code> | 0x0101 | First element of TCLK table |
| <code>ZCD_NV_TCLK_TABLE_END</code> | 0x01FF | Last element of TCLK table |
| <code>ZCD_NV_APS_LINK_KEY_DATA_START</code> | 0x0201 | First element of APS Link Key table |
| <code>ZCD_NV_APS_LINK_KEY_DATA_END</code> | 0x02FF | Last element of APS Link Key table |
| <code>ZCD_NV_MASTER_KEY_DATA_START</code> | 0x0301 | First element of Master Key table |
| <code>ZCD_NV_MASTER_KEY_DATA_END</code> | 0x03FF | Last element of Master Key table |

10.7 Quick Reference

| | |
|---|---|
| Enabling security | Set <code>SECURE = 1</code> (in <code>f8wConfig.cfg</code>) |
| Enabling preconfigured Network key | Set <code>zgPreConfigKeys = TRUE</code> (in <code>ZGlobals.c</code>) |
| Setting preconfigured Network key | Set <code>defaultKey = {KEY}</code> (in <code>nwk_globals.c</code>) |
| Enabling/disabling joining permissions on the Trust Center | Call <code>ZDSecMgrPermitJoining()</code> (in <code>ZDSecMgr.c</code>) |
| Specific device validation during joining | Modify <code>ZDSecMgrDeviceValidate</code> (in <code>ZDSecMgr.c</code>) |
| Network key updates | Call <code>ZDSecMgrUpdateNwkKey()</code> and <code>ZDSecMgrSwitchNwkKey()</code> (in <code>ZDSecMgr.c</code>) |
| Enabling Smart Energy Secure Joining with Pre-Configured Trust Center Link Keys | Set <code>SECURE = 1</code> (in <code>f8wConfig.cfg</code>) and include <code>SE_PROFILE</code> as a compile flag. |
| Use single(default) Preconfigured Trust Center Link Key | Set <code>zgUseDefaultTCLK=TRUE</code> (in <code>ZGlobals.c</code>). The NV item for this global is <code>ZCD_NV_USE_DEFAULT_TCLK</code> (defined in <code>ZComDef.h</code>). |
| Use multiple Preconfigured Trust Center Link Keys | Set <code>zgUseDefaultTCLK=FALSE</code> (in <code>ZGlobals.c</code>). The NV item for this global is <code>ZCD_NV_USE_DEFAULT_TCLK</code> (in <code>ZComDef.h</code>). Configure a preconfigured trust center link key for each device joining the network via <code>SYS_OSAL_NV_WRITE</code> . |

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 PANID (EPID) to find the network. If the extended PANID is found on different channels, the device selects the channel with the higher value in the *nwkUpdateId* parameter. If the extended PANID 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 <code>ZDNWKMGR_MIN_TRANSMISSIONS</code> (in <code>ZDNwkMgr.h</code>) |
| Setting minimum transmit failure rate for Channel Interference detection | Set <code>ZDNWKMGR_CI_TX_FAILURE</code> (in <code>ZDNwkMgr.h</code>) |
| Setting minimum transmit failure rate for Channel Change | Set <code>ZDNWKMGR_CC_TX_FAILURE</code> (in <code>ZDNwkMgr.h</code>) |
| Setting acceptable energy level threshold for Channel Change | Set <code>ZDNWKMGR_ACCEPTABLE_ENERGY_LEVEL</code> (in <code>ZDNwkMgr.h</code>) |
| Setting APS channel timer for issuing Channel Changes | Set <code>ZDNWKMGR_UPDATE_REQUEST_TIMER</code> (in <code>ZDNwkMgr.h</code>) |

11.3 PAN ID Conflict

Since the 16-bit PANID 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 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 of the following criteria:

- The current communication channel is different than 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: <ul style="list-style-type: none"> • 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 LQ 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 'derate' 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" 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.