QualNet 6.1
Sensor Networks Model Library

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1 Overview of Model Library

1.1 List of Models in the Library

The models described in the Sensor Networks Model Library are listed in Table 1-1.

TABLE 1-1. Sensor Networks Library Models

Model Name	Model Type	Section Number
ZigBee Application	Application Layer	Section 4.1
ZigBee MAC Model	MAC Layer	Section 3.1
ZigBee PHY Model	PHY Layer	Section 2.1

1.2 Sensor Networks - Overview

ZigBee is a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4 standard for Wireless Personal Area Networks (WPANs). ZigBee is targeted at RF applications that require a low data rate, long battery life, and secure networking. These networks are aimed at automation, remote control, and Wireless Sensor Network (WSN) applications. The IEEE 802.15.4 standard defines the physical layer (PHY) and Medium Access Control sublayer (MAC) specifications as the wireless communication standard for low-power consumption, Low-Rate WPAN (LR-WPANs).

The Sensor Networks Model Library consists of the following models:

- ZigBee Application
- ZigBee (IEEE 802.15.4) MAC
- ZigBee (IEEE 802.15.4) PHY

1.3 Conventions Used

1.3.1 Format for Command Line Configuration

This section describes the general format for specifying parameters in input files, the precedence rules for parameters, and the conventions used in the description of command line configuration for each model.

1.3.1.1 General Format of Parameter Declaration

The general format for specifying a parameter in an input file is:

```
[<Qualifier>] <Parameter Name> [<Index>] <Parameter Value>
```

where

`<Qualifier>` The qualifier is optional and defines the scope of the parameter declaration. The scope can be one of the following: Global, Node, Subnet, and Interface. Multiple instances of a parameter with different qualifiers can be included in an input file. Precedence rules (see Section 1.3.1.2) determine the parameter value for a node or interface.

Global: The parameter declaration is applicable to the entire scenario (to all nodes and interfaces), subject to precedence rules. The scope of a parameter declaration is global if the qualifier is not included in the declaration.

Example:

```
MAC-PROTOCOL            MACDOT11
```

Node: The parameter declaration is applicable to specified nodes, subject to precedence rules. The qualifier for a node-level declaration is a list of space-separated node IDs or a range of node IDs (specified by using the keyword `thru`) enclosed in square brackets.

Example:

```
[5 thru 10] MAC-PROTOCOL            MACDOT11
```

Subnet: The parameter declaration is applicable to all interfaces in specified subnets, subject to precedence rules. The qualifier for a subnet-level declaration is a space-separated list of subnet addresses enclosed in square brackets. A subnet address can be specified in the IP dot notation or in the QualNet N syntax.

Example:

```
[N8-1.0 N2-1.0] MAC-PROTOCOL       MACDOT11
```

Interface: The parameter declaration is applicable to specified interfaces. The qualifier for an interface-level declaration is a space-separated list of subnet addresses enclosed in square brackets.

Example:

```
[192.168.2.1 192.168.2.4] MAC-PROTOCOL MACDOT11
```

`<Parameter Name>`	Name of the parameter.
`<Index>`	Instance of the parameter to which this parameter declaration is applicable, enclosed in square brackets. This should be in the range 0 to *n* -1, where *n* is the number of instances of the parameter. The instance specification is optional in a parameter declaration. If an instance is not included, then the parameter declaration is applicable to all instances of the parameter, unless otherwise specified.
`<Parameter Value>`	Value of the parameter.

Note: There should not be any spaces between the parameter name and the index.

Examples of parameter declarations in input files are:

```
PHY-MODEL                                          PHY802.11b
[1] PHY-MODEL                                      PHY802.11a
[N8-1.0] PHY-RX-MODEL                              BER-BASED
[8 thru 10] ROUTING-PROTOCOL                       RIP
[192.168.2.1 192.168.2.4] MAC-PROTOCOL             GENERICMAC
NODE-POSITION-FILE                                 ./default.nodes
PROPAGATION-CHANNEL-FREQUENCY[0]                   2.4e9
[1 2] QUEUE-WEIGHT[1]                              0.3
```

Note: In the rest of this document, we will not use the qualifier or the index in a parameter's description. Users should use a qualifier and/or index to restrict the scope of a parameter, as appropriate.

1.3.1.2 Precedence Rules

Parameters without Instances

If the parameter declarations do not include instances, then the following rules of precedence apply when determining the parameter values for specific nodes and interfaces:

Interface > Subnet > Node > Global

This can be interpreted as follows:

- The value specified for an interface takes precedence over the value specified for a subnet, if any.
- The value specified for a subnet takes precedence over the value specified for a node, if any.
- The value specified for a node takes precedence over the value specified for the scenario (global value), if any.

Parameters with Instances

If the parameter declarations are a combination of declarations with and without instances, then the following precedence rules apply (unless otherwise stated):

Interface[i] > Subnet[i] > Node[i] > Global[i] > Interface > Subnet > Node > Global

This can be interpreted as follows:

- Values specified for a specific instance (at the interface, subnet, node, or global level) take precedence over values specified without the instance.
- For values specified for the same instance at different levels, the following precedence rules apply:
  - The value specified for an interface takes precedence over the value specified for a subnet, if any, if both declarations are for the same instance.
  - The value specified for a subnet takes precedence over the value specified for a node, if any, if both declarations are for the same instance.
  - The value specified for a node takes precedence over the value specified for the scenario (global value), if any, if both declarations are for the same instance.

1.3.1.3 Parameter Description Format

In the Model Library, most parameters are described using a tabular format described below. The parameter description tables have three columns labeled “Parameter”, “Values”, and “Description”. Table 1-2 shows the format of parameter tables. Table 1-4 shows examples of parameter descriptions in this format.

TABLE 1-2. Parameter Table Format

Parameter	Values	Description
<Parameter Name> <Designation> <Scope> [<Instances>]	*<Type>* [<Range>] [<Default Value>] [<Unit>]	*<Description>*

Parameter Column

The first column contains the following entries:

- ***<Parameter Name>*:** The first entry is the parameter name (this is the exact name of the parameter to be used in the input files).
- ***<Designation>:*** This entry can be *Optional* or *Required*. These terms are explained below.
  - ***Optional***: This indicates that the parameter is optional and may be omitted from the configuration file. (If applicable, the default value for this parameter is included in the second column.)
  - ***Required***: This indicates that the parameter is mandatory and must be included in the configuration file.
- ***<Scope>:*** This entry specifies the possible scope of the parameter, i.e., if the parameter can be specified at the global, node, subnet, or interface levels. Any combination of these levels is possible.If the parameter can be specified at all four levels, the keyword “All” is used to indicate that.

Examples of scope specification are:

Scope: All

Scope: Subnet, Interface

Scope: Global, Node

- ***<Instances>:*** If the parameter can have multiple instances, this entry indicates the type of index. If the parameter can not have multiple instances, then this entry is omitted.

Examples of instance specification are:

Instances: channel number

Instances: interface index

Instances: queue index

Values Column

The second column contains the following information:

- ***<Type>*:** The first entry is the parameter type and can be one of the following: Integer, Real, String, Time, Filename, IP Address, Coordinates, Node-list, or List. If the type is a List, then all possible values in the list are enumerated below the word “List”. (In some cases, the values are listed in a separate table and a reference to that table is included in place of the enumeration.)

  Table 1-3 shows the values a parameter can take for each type.

TABLE 1-3. Parameter Types

Type	Description
Integer	Integer value Examples: `2`, `10`
Real	Real value Examples: `15.0`, `-23.5`, `2.0e9`
String	String value Examples: `TEST`, `SWITCH1`
Time	Time value expressed in QualNet time syntax (refer to *QualNet User’s Guide*) Examples: `1.5S`, `200MS`, `10US`

Filename	Name of a file in QualNet filename syntax (refer to *QualNet User’s Guide*)
	Examples:
	`../../data/terrain/los-angeles-w`
	(For Windows and UNIX)
	`C:\snt\qualnet\6.1\scenarios\WF\WF.nodes`
	(For Windows)
	`/root/snt/qualnet/6.1/scenarios/WF/WF.nodes`
	(For UNIX)

TABLE 1-3. Parameter Types (Continued)

Type	Description
Path	Path to a directory in QualNet path syntax (refer to *QualNet User's Guide*) Examples: `../../data/terrain` (For Windows and UNIX) `C:\snt\qualnet\6.1\scenarios\default` (For Windows) `/root/snt/qualnet/6.1/scenarios/default` (For UNIX)
IP Address	IPv4 or IPv6 address Examples: `192.168.2.1`, `2000:0:0:0::1`
IPv4 Address	IPv4 address Examples: `192.168.2.1`
IPv6 Address	IPv6 address Examples: `2000:0:0:0::1`
Coordinates	Coordinates in Cartesian or Lat-Lon-Alt system. The altitude is optional. Examples: `(100, 200, 2.5)`, `(-25.3478, 25.28976)`
Node-list	List of node IDs separated by commas and enclosed in "`{`" and "`}`". Examples: `{2, 5, 10}`, `{1, 3 thru 6}`
List	One of the enumerated values. Example: See the parameter `MOBILITY` in Table 1-4.

Note: If the parameter type is List, then options for the parameter available in QualNet and the commonly used model libraries are enumerated. Additional options for the parameter may be available if some other model libraries or addons are installed. These additional options are not listed in this document but are described in the corresponding model library or addon documentation.

- ***<Range>*:** This is an optional entry and is used if the range of values that a parameter can take is restricted. The permissible range is listed after the label "*Range:*" The range can be specified by giving the minimum value, the maximum value, or both. If the range of values is not restricted, then this entry is omitted.

  If both the minimum and maximum values are specified, then the following convention is used to indicate whether the minimum and maximum values are included in the range:

`(min, max)`	`min` < parameter value < `max`
`[min, max)`	`min` ≤ parameter value < `max`
`(min, max]`	`min` < parameter value ≤ `max`
`[min, max]`	`min` ≤ parameter value ≤ `max`

`min` (or `max)` can be a parameter name, in which case it denotes the value of that parameter.

Examples of range specification are:

Range: ≥ `0`

Range: `(0.0, 1.0]`

Range: `[1, MAX-COUNT]`

Range: `[1S, 200S]`

Note: If an upper limit is not specified in the range, then the maximum value that the parameter can take is the largest value of the type (integer, real, time) that can be stored in the system.

- ***<Default>*:** This is an optional entry which specifies the default value of an optional or conditional-optional parameter. The default value is listed after the label "*Default:*"
- ***<Unit>*:** This is an optional entry which specifies the unit for the parameter, if applicable. The unit is listed after the label "*Unit:*". Examples of units are: meters, dBm, slots.

Description Column

The third column contains a description of the parameter. The significance of different parameter values is explained here, where applicable. In some cases, references to notes, other tables, sections in the User's Guide, or to other model libraries may be included here.

Table 1-4 shows examples of parameter descriptions using the format described above.

TABLE 1-4. Example Parameter Table

Parameter	Values	Description
`MOBILITY` Optional *Scope:* Global, Node	List: • `NONE` • `FILE` • `GROUP-MOBILITY` • `RANDOM-WAYPOINT` *Default:* `NONE`:	Mobility model used for the node. If `MOBILITY` is set to `NONE`, then the nodes remain fixed in one place for the duration of the simulation. See Table 7-11 for a description of mobility models.
`BACKOFF-LIMIT` Required *Scope:* Subnet, Interface	Integer *Range:* `[4,10)` *Unit:* slots	Upper limit of backoff interval after collision. A backoff interval is randomly chosen between 1 and this number following a collision.

TABLE 1-4. Example Parameter Table (Continued)

Parameter	Values	Description
`IP-QUEUE-PRIORITY-QUEUE-SIZE` Required *Scope:* All *Instances:* queue index	Integer *Range:* `[1, 65535]` *Unit:* bytes	Size of the output priority queue.
`MAC-DOT11-DIRECTIONAL-ANTENNA-MODE` Optional *Scope:* All	List • `YES` • `NO` *Default:* `NO`	Indicates whether the radio is to use a directional antenna for transmission and reception.

1.3.2 Format for GUI Configuration

The GUI configuration section for a model outlines the steps to configure the model using the GUI. The following conventions are used in the GUI configuration sections:

Path to a Parameter Group

As a shorthand, the location of a parameter group in a properties editor is represented as a path consisting of the name of the properties editor, name of the tab within the properties editor, name of the parameter group within the tab (if applicable), name of the parameter sub-group (if applicable), and so on.

Example

The following statement:

Go to **Default Device Properties Editor > Interfaces > Interface # > MAC Layer**

is equivalent to the following sequence of steps:

1. Open the Default Device Properties Editor for the node.
2. Click the **Interfaces** tab.
3. Expand the applicable Interface group.
4. Click the **MAC Layer** parameter group.

The above path is shown in Figure 1-1.

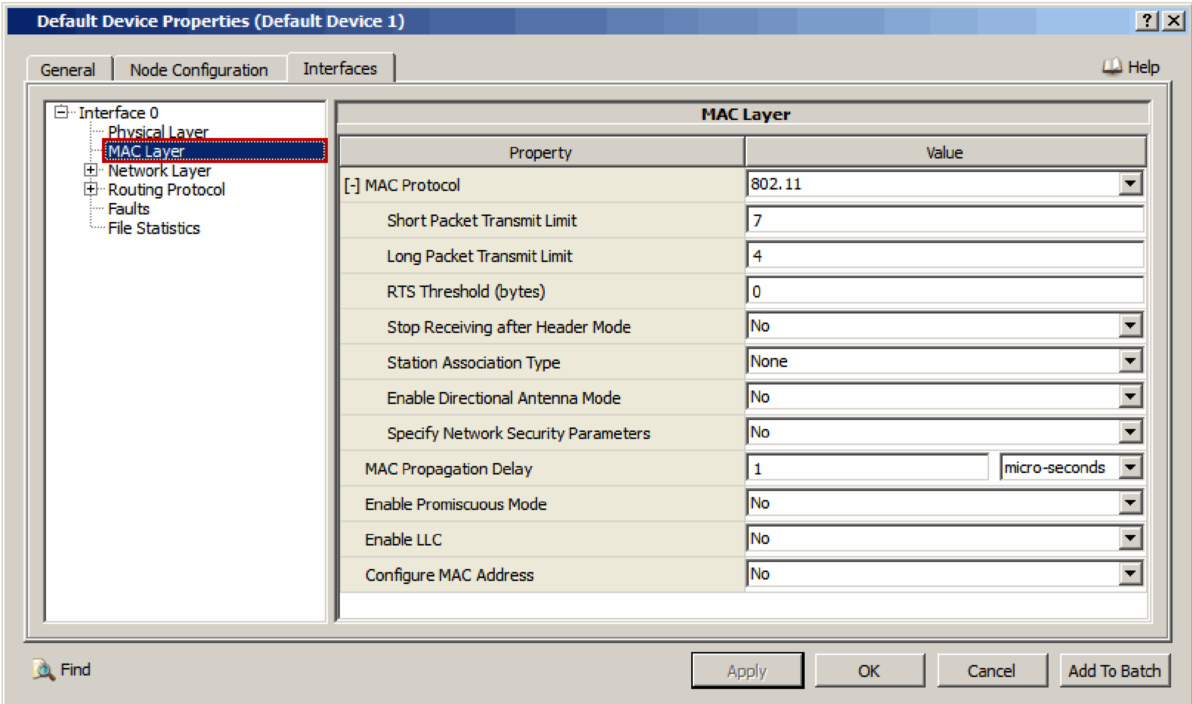

FIGURE 1-1. Path to a Parameter Group

Path to a Specific Parameter

As a shorthand, the location of a specific parameter within a parameter group is represented as a path consisting of all ancestor parameters and their corresponding values starting from the top-level parameter. The value of an ancestor parameter is enclosed in square brackets after the parameter name.

Example

The following statement:

Set **MAC Protocol** *[= 802.11]* **> Station Association Type** *[= Dynamic]* **> Set Access Point** *[= Yes]* **>** *Enable Power Save Mode* to *Yes*

is equivalent to the following sequence of steps:

1. Set **MAC Protocol** to *802.11*.
2. Set **Station Association Type** to *Dynamic.*
3. Set **Set Access Point** to *Yes*.
4. Set **Enable Power Save Mode** to *Yes*.

The above path is shown in Figure 1-2.

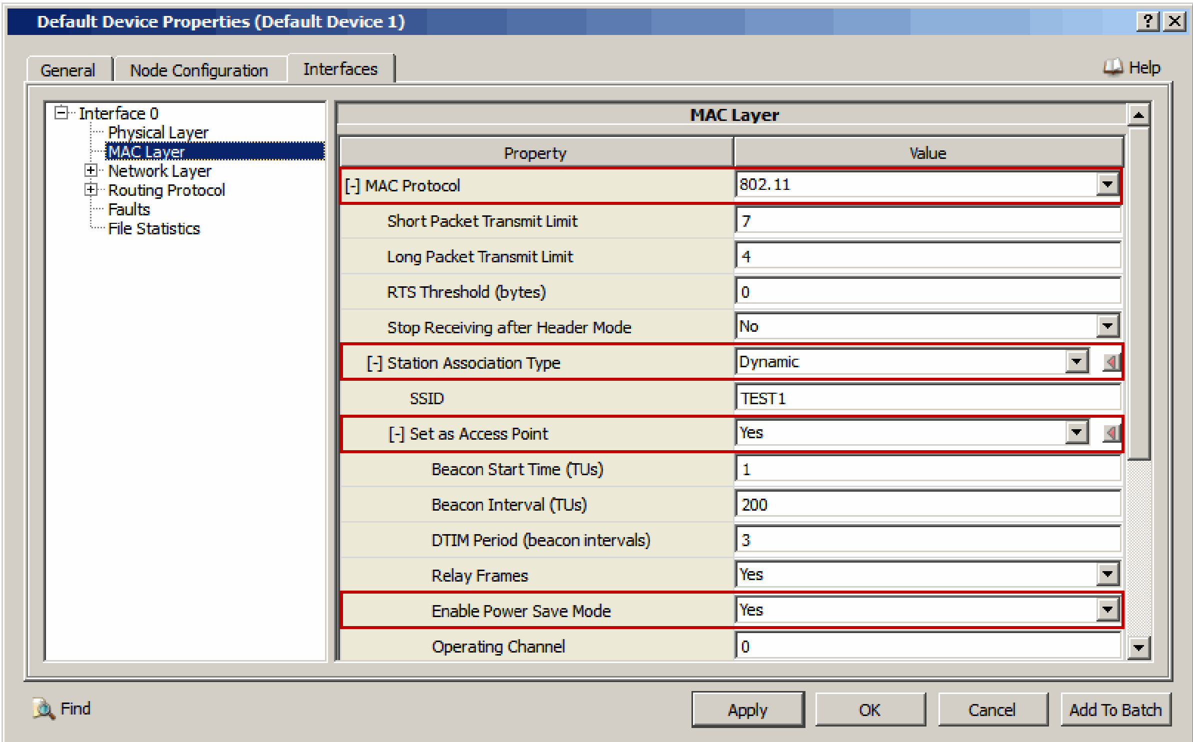

FIGURE 1-2. Path to a Specific Parameter

Parameter Table

GUI configuration of a model is described as a series of a steps. Each step describes how to configure one or more parameters. Since the GUI display name of a parameter may be different from the name in the configuration file, each step also includes a table that shows the mapping between the GUI names and command line names of parameters configured in that step. For a description of a GUI parameter, see the description of the equivalent command line parameter in the command line configuration section.

The format of a parameter mapping table is shown in Table 1-5.

TABLE 1-5. Mapping Table

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
<GUI Display Name>	*<Scope>*	*<Command Line Parameter Name>*

The first column, labeled "GUI Parameter", lists the name of the parameter as it is displayed in the GUI.

The second column, labeled "Scope of GUI Parameter", lists the level(s) at which the parameter can be configured. *<Scope>* can be any combination of: Global, Node, Subnet, Wired Subnet, Wireless Subnet, Point-to-point Link, and Interface.

Table 1-6 lists the Properties Editors where parameters with different scopes can be set.

Notes: **1.** Unless otherwise stated, the “Subnet” scope refers to “Wireless Subnet”.

2. The scope column can also refer to Properties Editors for special devices and network components (such as ATM Device Properties Editor) which are not included in Table 1-6.

TABLE 1-6. Properties Editors for Different Scopes

Scope of GUI Parameter	Properties Editor
Global	Scenario Properties Editor
Node	Default Device Properties Editor (General and Node Configuration tabs)
Subnet Wireless Subnet	Wireless Subnet Properties Editor
Wired Subnet	Wired Subnet Properties Editor
Point-to-point Link	Point-to-point Link Properties Editor
Interface	Interface Properties Editor, Default Device Properties Editor (Interfaces tab)

The third column, labeled “Command Line Parameter”, lists the equivalent command line parameter.

Note: For some parameters, the scope may be different in command line and GUI configurations (a parameter may be configurable at fewer levels in the GUI than in the command line).

Table 1-7 is an example of a parameter mapping table.

TABLE 1-7. Example Mapping Table

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Define Area	Node	`OSPFv2-DEFINE-AREA`
OSPFv2 Configuration File	Node	`OSPFv2-CONFIG-FILE`
Specify Autonomous System	Node	N/A
Configure as Autonomous System Boundary Router	Node	`AS-BOUNDARY-ROUTER`
Inject External Route	Node	N/A
Enable Stagger Start	Node	`OSPFv2-STAGGER-START`

2 PHY Layer Models

This chapter describes features, configuration requirements and parameters, statistics, and scenarios for PHY Layer Models in the Sensor Networks Model Library, and consists of the following section:

- ZigBee PHY Model

2.1 ZigBee PHY

The QualNet ZigBee PHY is based on the IEEE 802.15.4-2006 standard.

2.1.1 Description

The PHY layer provides an interface between the MAC layer and the physical radio channel. It provides two services, accessed through two service access points (SAPs). These are the PHY data service and the PHY management service. The PHY layer is responsible for the following tasks:

- **Activation and deactivation of the radio transceiver**

  Turn the radio transceiver into one of the three states,(i.e., transmitting, receiving, or off (sleeping)) according to the request from MAC sublayer. The turnaround time from transmitting to receiving, or vice versa, should be not more than 12 symbol periods.

- **Energy Detection (ED) within the current channel**

  It is an estimate of the received signal power within the bandwidth of an IEEE 802.15.4 channel. No attempt is made to identify or decode signals on the channel in this procedure. The energy detection time shall be equal to 8 symbol periods. The result from energy detection can be used by a network layer as part of a channel selection algorithm, or for the purpose of clear channel assessment (CCA) (alone or combined with carrier sense).

- **Link Quality Indication (LQI) for received packets**

  Link quality indication measurement is performed for each received packet. The PHY layer uses receiver energy detection (ED), a signal-to-noise ratio, or a combination of these to measure the strength and the quality of a link from which a packet is received. However, the use of LQI result by the network or application layers is not specified in the standard.

- **Clear Channel Assessment (CCA) for Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA)**

  The PHY layer is required to perform CCA using energy detection, carrier sense, or a combination of these two. In energy detection mode, the medium is considered busy if any energy above a predefined energy threshold is detected. In carrier sense mode, the medium is considered busy if a signal with the modulation and spreading characteristics of IEEE 802.15.4 is detected. And in the combined mode, both conditions aforementioned need to be met in order to conclude that the medium is busy.

- **Channel frequency selection**

  Wireless links under 802.15.4 can operate in 27 different channels (but a specific network can choose to support part of the channels). Hence the PHY layer should be able to tune its transceiver into a certain channel upon receiving the request from MAC sublayer.

- **Data transmission and reception**

  This is the essential task of the PHY layer. Modulation and spreading techniques are used in this part. The 2.4 GHz PHY employs a 16-ary quasi-orthogonal modulation technique, in which each four information bits are mapped into a 32-chip pseudo-random noise (PN) sequence. The PN sequences for successive data symbols are concatenated and modulated onto the carrier using offset quadrature phase shift 3 keying (O-QPSK). The 868/915 MHz PHY employs direct sequence spread spectrum (DSSS) with binary phase shift keying (BPSK) used for chip modulation and differential encoding used for data symbol encoding. Each data symbol is mapped into a 15-chip PN sequence and the concatenated PN sequences are then modulated onto the carrier using BPSK with raised cosine pulse shaping.

Physical Layer: Modulations Schemes and Operational Frequencies

The IEEE 802.15.4 standard specifies the multiple PHYs for 868, 915 and 2400 MHz three frequency bands. They use different modulation schemes and different spread spectrum methods to transmit data in different data rates with different chip rates. There are total 37 channels with different bandwidth specified in the standard, which includes one channel in 868 MHz frequency band and 10 channels in 915 MHz frequency band and 16 channels in 2.4 GHz frequency band. The standard specifies the following mandatory multiple PHYs:

- An 868/915 MHz direct sequence spread spectrum (DSSS) PHY employing binary phase-shift keying (BPSK) modulation
- A 2450 MHz DSSS PHY employing O-QPSK modulation

In addition, other than the mandatory PHYs above, the following optional PHYs are also specified in the standard:

- An 868/915 MHz parallel sequence spread spectrum (PSSS) PHY employing amplitude shift keying (ASK) modulation
- An 868/915 MHz DSSS PHY employing offset quadrature phase-shift keying (O-QPSK) modulation

In the mandatory PHYs, The 868/915 MHz BPSK PHY use DSSS with BPSK used for chip modulation and differential encoding used for data symbol encoding to provide 20 kb/s raw data rate in the 800 MHz band and 40 kb/s raw data rate in the 900 MHz band with chip rate in 300 kchip/s and 600 kchip/s respectively.

The 2450 MHz DSSS PHY employs DSSS with a 16-ary quasi-orthogonal (O-QPSK) modulation scheme to provide 250 kb/s raw data rate with 2000 kchip/s of chip rate within the specified 2 MHz bandwidth.

In the optional PHYs, the 868/915 MHz ASK PHY are using PSSS with ASK modulation scheme that offers raw data rates of 250 kb/s in both the 868 MHz and 915 MHz bands with chip rate of 400 and 1600 kchip/s respectively.

The 868/915 MHz O-QPSK PHY employs DSSS with a 16-ary quasi-orthogonal (O-QPSK) modulation technique to offer a data rate of 100 kb/s in the 868 MHz band and a data rate of 250 kb/s in the 915 MHz band with the chip rate of 400 and 1000 kchip/s respectively.

Table 2-1 lists the frequency bands and the related modulation schemes and the supported data rates. Note that the chip rate in the table is the transmission rate in air after spectrum spread while the bit rate is the raw data rate supported for the applications. In general, the end-to-end throughput should be less than the bit rates listed in the table.

TABLE 2-1. Frequency Bands and Data Rates

PHY (MHz)	Frequency Band (MHz)	Spreading Parameters		Data Parameters		
		Chip Rate (kchip/s)	Modulation	Bit Rate (kb/s)	Symbol Rate (ksymbol/s)	Symbols
868/915	868-868.6	300	BPSK	20	20	Binary
	902-928	600	BPSK	40	40	Binary
868/915 (optional)	868-868.6	400	ASK	250	12.5	20-bit PSSS
	902-928	1600	ASK	250	50	5-bit PSSS

TABLE 2-1. Frequency Bands and Data Rates (Continued)

PHY (MHz)	Frequency Band (MHz)	Spreading Parameters		Data Parameters		
		Chip Rate (kchip/s)	Modulation	Bit Rate (kb/s)	Symbol Rate (ksymbol/s)	Symbols
868/915 (optional)	868-868.6	400	O-QPSK	100	25	16-ary Orthogonal
	902-928	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2400-2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

All mandatory and optional PHYs specified in the standard are implemented in this implementation. The PHYs working in different frequency bands with different channel bandwidths, different combinations of modulation schemes and spread spectrums methods as specified in the standard are supported.

2.1.2 Features and Assumptions

This section describes the implemented features, omitted features, assumptions and limitations of the ZigBee PHY model.

2.1.2.1 Implemented Features

- 800, 900, and 2400 MHz multiple frequency bands support.
- Multiple combinations of modulation schemes and spread spectrum support.
- BER based reception quality estimation.
- Energy detection.
- Link quality indication.
- Clear channel assessment

2.1.2.2 Omitted Features

- Multiple interface support

2.1.2.3 Assumptions and Limitations

- PHY layer supports only a single channel

2.1.3 Supplemental Information

None.

2.1.4 Command Line Configuration

To specify ZigBee PHY as the PHY protocol, include the following parameter in the scenario configuration (.config) file:

```
[<Qualifier>]   PHY-MODEL      PHY802.15.4
```

The scope of this parameter declaration can be Global, Node, Subnet, or Interface. See Section 1.3.1.1 for a description of `<Qualifier>` for each scope.

Configuration Requirements

To use ZigBee PHY as the PHY protocol, the MAC protocol must be configured to be ZigBee MAC. See Section 3.1 for details of configuring ZigBee MAC.

ZigBee PHY Parameters

Table 2-2 lists the ZigBee PHY parameters specified in the scenario configuration (.config) file. See Section 1.3.1.3 for a description of the format used for the parameter table.

TABLE 2-2. ZigBee PHY Parameters

Parameter	Value	Description
PHY802.15.4-TX-POWER *Optional* *Scope:* All	Real *Default:* 0.0 *Unit:* dBm	This parameter specifies the power to transmit (in dBm). There is no theoretical bound for the maximum value; however, it should be the reasonable value according to the scenario or device specifications.
PHY802.15.4-MODULATION *Optional* *Scope:* All	List: • O-QPSK • ASK • BPSK *Default:* O_QPSK	This parameter specifies the modulation scheme to be used by the PHY model. As specified in the standard, O-QPSK is suitable for three frequency bands while ASK and BPSK can only be supported in 800 and 900 MHz bands.
PHY802.15.4-CCA-MODE *Optional* *Scope:* All	List: • CARRIER-SENSE • CARRIER-SENSE-WITH-ENERGY-ABOVE-THRESHOLD • ENERGY-ABOVE-THRESHOLD *Default:* CARRIER-SENSE	This parameter specifies the Clear Channel Assessment (CCA) method. If this parameter is set to ENERGY-ABOVE-THRESHOLD, CCA shall report a busy medium upon detecting any energy above the specified energy detection threshold. If this parameter is set to CARRIER-SENSE, CCA shall report a busy medium only upon the detection of a signal with the same modulation and spreading characteristics of the PHY that is currently in use and this signal may be above or below the energy detection threshold. If this parameter is set to CARRIER-SENSE-WITH-ENERGY-ABOVE-THRESHOLD, CCA shall report a busy medium using a logical combination of detection of a signal with the modulation and spreading characteristics that the PHY is currently in use and Energy above the energy detection threshold.
PHY-RX-MODEL *Required* *Scope:* All	List: • PHY802.15.4 • BER-BASED	Specifies the packet reception model.
PHY-LAYER-STATISTICS *Optional* *Scope:* All	List: • YES • NO *Default:* NO	Indicates whether statistics are collected for the physical layer protocols, including ZigBee PHY.

In addition to parameters described in Table 2-2, several other simulation parameters have a significant effect on the performance, such as noise factor, antenna gain, frequency, pathloss, shadowing and fading model. Specify values for these parameters most suitable for the scenario.

Note: The current implementation supports only the omnidirectional antenna model.

2.1.5 GUI Configuration

This section describes how to configure the ZigBee PHY model in the GUI.

Configuration Requirements

To use ZigBee PHY as the PHY protocol, the MAC protocol must be configured to be ZigBee MAC. See Section 3.1 for details of configuring ZigBee MAC.

Configuring ZigBee PHY Model Parameters

To configure the general ZigBee PHY parameters, perform the following steps:

1. Go to one of the following locations:
   - To set properties at the wireless subnet level, go to **Wireless Subnet Properties Editor > Physical Layer**.
   - To set properties at the interface level, go to one of the following locations:
     - **Interface Properties Editor > Interfaces > Interface # > Physical Layer**.
     - **Default Device Properties Editor > Interfaces > Interface # > Physical Layer**.

   In this section, we show how to configure ZigBee PHY parameters for a specific interface using the Default Device Properties Editor. Parameters can be set in the other properties editors in a similar way.

2. Set **Radio Type** to *802.15.4 Radio* and set the dependent parameters listed in Table 2-3.

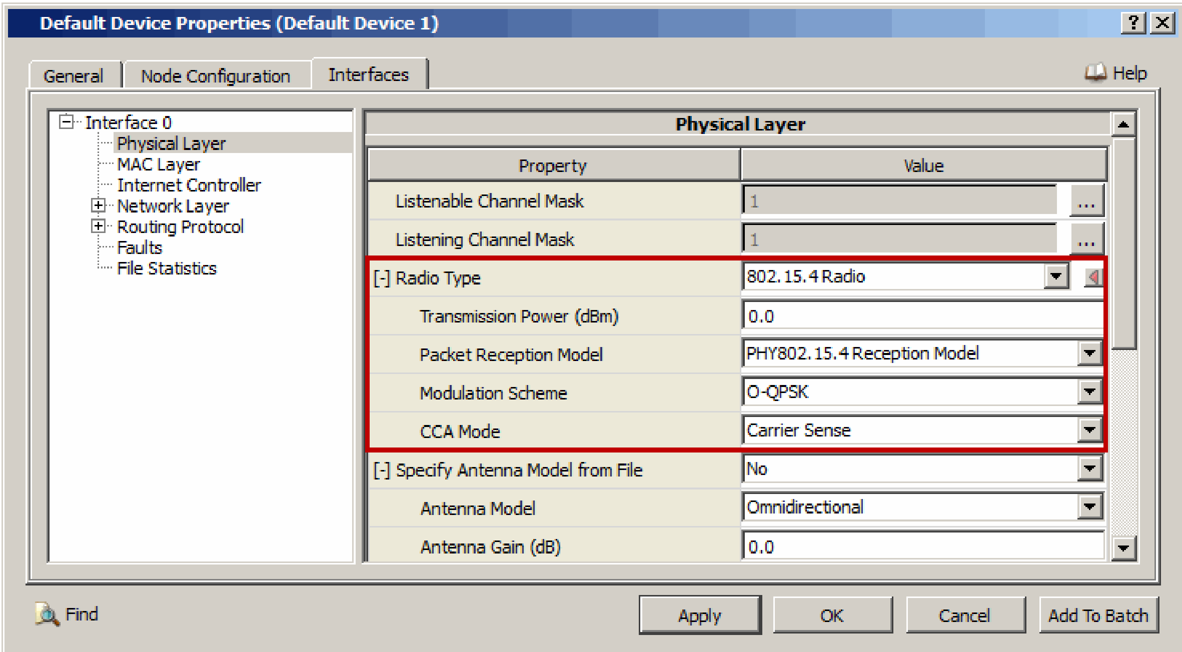

FIGURE 2-1. Setting ZigBee PHY Parameters

TABLE 2-3. Command Line Equivalent of ZigBee PHY Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Transmission Power	Subnet, Interface	`PHY802.15.4-TX-POWER`
Packet Reception Model	Subnet, Interface	`PHY-RX-MODEL`
Modulation Scheme	Subnet, Interface	`PHY802.15.4-MODULATION`
CCA Mode	Subnet, Interface	`PHY802.15.4-CCA-MODE`

Setting Parameters

- If **Packet Reception Model** is set to *BER-based Reception Model*, then specify the names of the files contating the BER tables. Refer to *Wireless Model Library* for details of the BER-based reception model.

Configuring Statistics Parameters

Statistics for the ZigBeePHY model can be collected at the global, node, subnet, and interface levels. See Section 4.2.9 of *QualNet User's Guide* for details of configuring statistics parameters.

To enable statistics collection for ZigBee PHY, check the box labeled **PHY/Radio** in the appropriate properties editor.

TABLE 2-4. Command Line Equivalent of Statistics Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
PHY/Radio	Global, Node, Subnet, Interface	`PHY-LAYER-STATISTICS`

2.1.6 Statistics

This section describes the file and dynamic statistics of the ZigBee PHY model.

2.1.6.1 File Statistics

Table 2-5 lists the statistics collected for the ZigBee PHY model that are output to the statistics (.stat) file at the end of simulation.

TABLE 2-5. ZigBee PHY Statistics

Statistic	Explanation
Signals transmitted	Total number of signals transmitted by the node.
Signals detected	Total number of signal detected.
Signals locked on by PHY	Total number of signals locked on by PHY for the node.
Signals received and forwarded to MAC	Total number of signals received and forward to MAC by the node.
Signals received but with errors	Total number of signals in errors for the node.

2.1.6.2 Dynamic Statistics

The following dynamic statistics are enabled for the ZigBee PHY model (refer to Chapter 5 of *QualNet User's Guide* for details of viewing dynamic statistics in the GUI during the simulation):

- Number of Signals Transmitted
- Number of Signals Detected
- Number of Signals Locked onto
- Number of Signals Received with Errors
- Number of Signals Forwarded to MAC layer
- Signal-to-Noise Ratio (dB)
- Energy Consumption (mWhr)

2.1.7 Sample Scenario

2.1.7.1 Scenario Description

The sample scenario creates a simple scenario consisting of two nodes: node1, which is a FFD device, acts as PAN coordinator and node 2, which is RFD device, acts as end device. A CBR session is configured from node 1 to node 2.

Topology

Figure 2-2 shows the topology of the sample scenario.

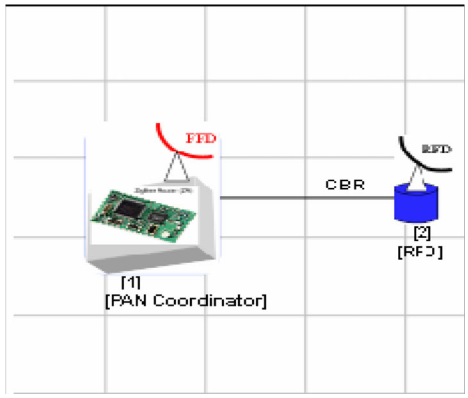

FIGURE 2-2. ZigBee Sample Scenario Topology

2.1.7.2 Command Line Configuration

Scenario Configuration File

1. Enable ZigBee MAC and PHY at nodes 1 and 2.

```
[ 1 2 ] MAC-PROTOCOL MAC802.15.4
[ 1 2 ] PHY-MODEL PHY802.15.4
```

2. Set reception model, transmit power, modulation type, and channel assessment method for nodes 1 and 2.

```
[ 1 2 ] PHY-RX-MODEL PHY802.15.4
[ 1 2 ] PHY802.15.4-TX-POWER 3.0
[ 1 2 ] PHY-RX-MODEL PHY802.15.4
[ 1 2 ] PHY802.15.4-MODULATION O-QPSK
[ 1 2 ] PHY802.15.4-CCA-MODE CARRIER-SENSE
```

3. Set device type for node 1 as FFD device (as PAN coordinator) and for node 2 as RFD device.

```
[ 1 ] MAC-802.15.4-DEVICE-TYPE FFD
[ 1 ] MAC-802.15.4-FFD-MODE PANCOORD
[ 2 ] MAC-802.15.4-DEVICE-TYPE RFD
```

4. Set poll interval for RFD device (node 2).

```
[ 2 ] MAC-802.15.4-POLL-INTERVAL 1S
```

5. Set the GTS parameter for the PAN coordinator (node 1).

```
[ 1 ] MAC-802.15.4-ENABLE-GTS  NO
```

6. Set the acknwoledgement parameters.

```
[ 1 2 ] MAC-802.15.4-ENABLE-DATA-ACKS  NO
```

7. Set beacon parameters.

```
[ 1 2 ] MAC-802.15.4-COORD-BO 3
[ 1 2 ] MAC-802.15.4-COORD-SO 3
```

8. Set device start/stop parameters.

```
[ 1 2 ] MAC-802.15.4-START-DEVICE-AT 0S
[ 1 2 ] MAC-802.15.4-STOP-DEVICE-AT 0S
```

9. Enable statistics collection.

```
[ 1 2 ] PHY-LAYER-STATISTICS   YES
[ 1 2 ] MAC-LAYER-STATISTICS   YES
```

2.1.7.3 GUI Configuration

Perform the following steps to create this sample scenario using the GUI:

1. Place two nodes of the Default device type and a wireless subnet on the canvas. Connect the nodes to the wireless subnet.

2. To configure ZigBee PHY at nodes 1 and 2, do the following:

   a. Go to the **Default Device Properties Editor > Interfaces > Interface # > Physical Layer**.

   b. Set **Radio Type** to *802.15.4 Radio* (see Figure 2-3).

   c. Set **Transmission Power** to *3.0*.

   d. Set **Packet Reception Model** to *PHY802.15.4 Reception Model*.

   e. Set **Modulation Scheme** to *O-QPSK*.

   f. Set **CCA Mode** to *Carrier Sense*.

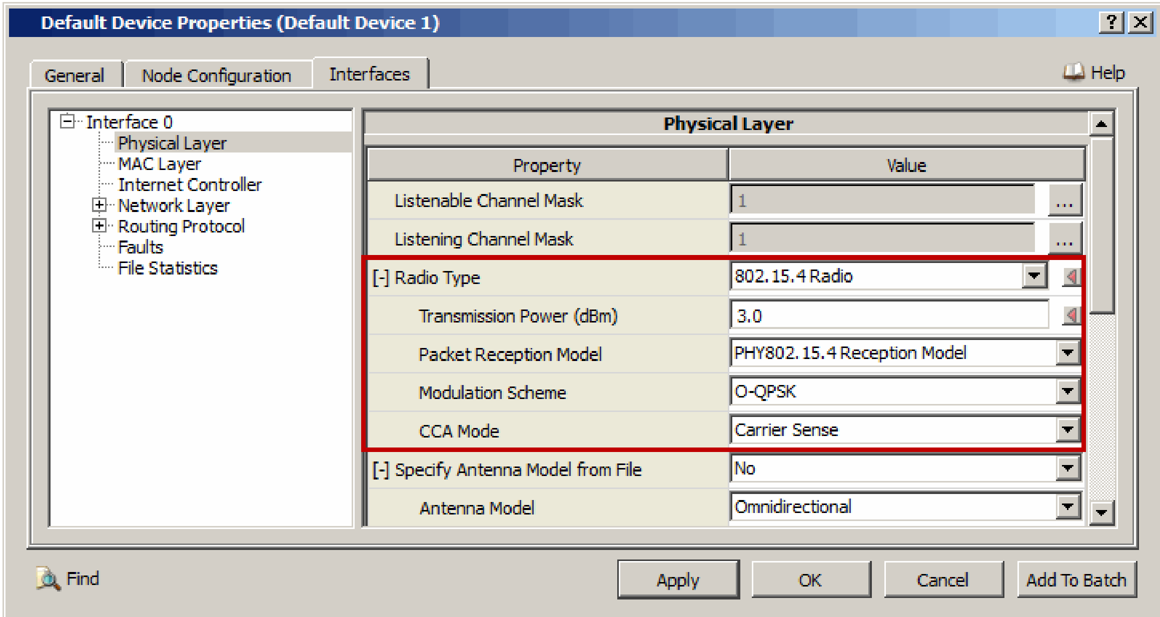

FIGURE 2-3. Setting Radio Parameters

3. To configure ZigBee MAC at node 1, do the following:
   a. Go to the **Default Device Properties Editor > Interfaces > Interface # > MAC Layer**.
   b. Set **MAC Protocol** to *802.15.4* (see Figure 2-4).
   c. Set **Device Type** to *Full Function Device (FFD)*.
   d. Set **FFD Mode** to *PAN Coordinator*.

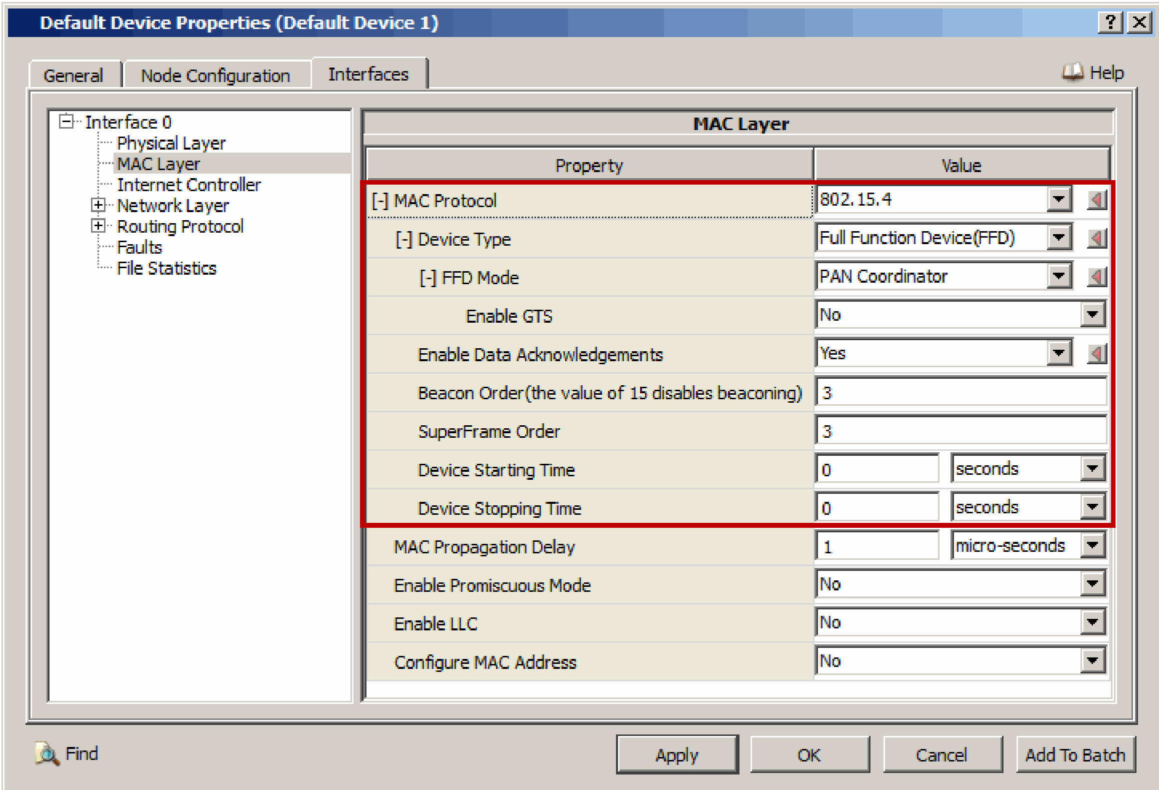

FIGURE 2-4. Setting MAC Parameters for Node 1

4. To configure ZigBee MAC at node 2, do the following:
   a. Go to the **Default Device Properties Editor > Interfaces > Interface # > MAC Layer**.
   b. Set **MAC Protocol** to *802.15.4* (see Figure 2-5).
   c. Set **Device Type** to *Reduced Function Device (RFD).*

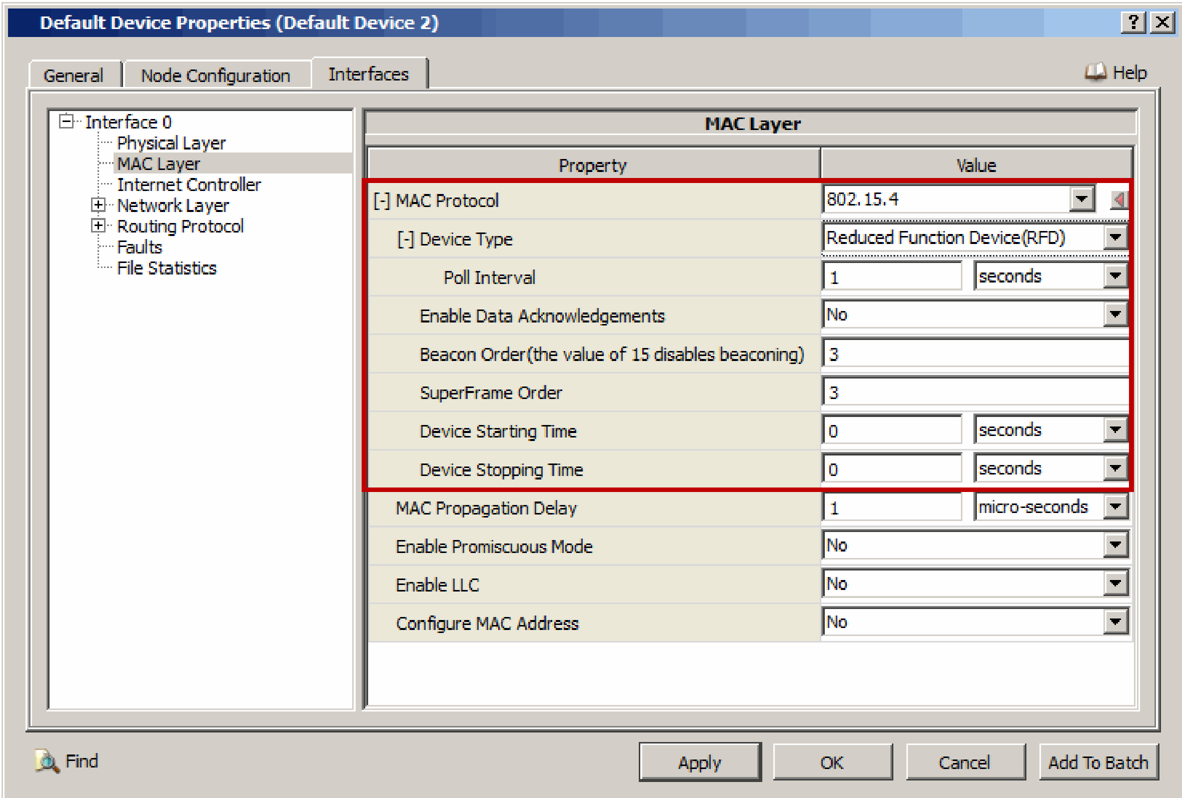

FIGURE 2-5. Setting MAC Parameters for Node 2

5. For nodes 1 and 2, go to **Default Device Properties Editor > Node Configuration > Routing Protocol**. Set **Routing Protocol IPv4** to *AODV* and set the dependent parameters.
6. To enable statistics collection, go to **Scenario Properties Editor > Statistics and Tracing > File Statistics**. Check the **MAC** and **PHY/Radio** boxes.

2.1.8 Scenarios Included in QualNet

The QualNet distribution includes several sample scenarios for the ZigBee PHY model. All scenarios are located in the directory QUALNET_HOME/scenarios/sensor_networks. Table 2-6 lists the sub-directory where each scenario is located.

TABLE 2-6. ZigBee PHY Model Scenarios

Scenario Sub-directory	Description
Battlefield Monitoring with Sensors	
BattlefieldMonitoringwithSensors	Demonstrates data collection from ground sensors using mobile vehicles.
ZigBee	
2-node	Demonstrates beacon generation, association and direct data transfer.

TABLE 2-6. ZigBee PHY Model Scenarios (Continued)

Scenario Sub-directory	Description
multi-app-at-same-time	Demonstrates multiple applications configured between RFD and PAN-Coordinator.
multiple-ffd	Demonstrates the behavior FFD, i.e., beacon generation and association with RFD.
nonbeacon-enable	Demonstrates the communication between devices in nonbeacon enabled mode.
orphaned-device	Demonstrates the behavior of a mobile device which is transmitting data packets and becomes disassociated (orphaned) from the PAN coordinator.
ZigBee Auto Home	
ZigBee-AutoHome	Demonstrates an application of ZigBee technology for Home Automation. It demonstrates the monitoring and control capability that can be achieved with ZigBee.
ZigBee GTS Feature	
transmit-receive-gts	Demonstrates the transmit Guatranteed Time Slot (GTS) and receive GTS functionality.
transmit-gts-expiry	Demonstrates the transmit GTS expiration functionality.
receive-gts-expiry	Demonstrates the receive GTS expiration functionality.

2.1.9 References

1. LAN-MAN Standards Committee of the IEEE Computer Society, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE, 2006
2. LAN-MAN Standards Committee of the IEEE Computer Society, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE, 2003
3. Sinem Coleri Ergen, "ZigBee/IEEE 802.15.4 Summary", September 2004
4. http://ees2cy.engr.ccny.cuny.edu/zheng/pub/ - CCNY Electrical Engineering Department's ZigBee implementation in ns-2.

3 MAC Layer Models

This chapter describes features, configuration requirements and parameters, statistics, and scenarios for MAC Layer Models in the Sensor Networks Model Library, and consists of the following section:

- ZigBee MAC Model

3.1 ZigBee MAC

The QualNet ZigBee MAC is based on the IEEE 802.15.4-2006 standard.

3.1.1 Description

The MAC sublayer of 802.15.4 defines how the medium should be accessed by devices participating in a WPAN. It provides two types of services: MAC data service through MAC Common Part Sublayer (MCPS) and MAC management service through MAC sub-Layer Management Entity (MLME).

PAN Information Base (PIB) comprises the attributes required to manage the MAC sublayer of a device.

The main features of a MAC sublayer are beacon management, channel access, Guaranteed Time Slot (GTS) management, frame validation, acknowledged frame delivery, association and disassociation, and device security.

The MAC layer provides an interface between the Service Specific Convergence Sublayer (SSCS) and the PHY layer. Like the PHY layer, the MAC layer also provides two services, namely, the MAC data service and the MAC management service.

A brief description of the MAC features is as follows:

- **Generating network beacons if the device is a coordinator**

  A coordinator can determine whether to work in a beacon enabled mode, in which a superframe structure is used. The superframe is bounded by network beacons and divided into slots of equal size. By default, the number of slots is 16. A coordinator sends out beacons periodically to synchronize the attached devices and for other purposes. A Full Function Device (FFD), that is not the PAN coordinator should begin transmitting beacon frames only when it has successfully associated with a PAN.

  The Superframe is divided into active and inactive periods. Active period is further divided into Contention Access Period (CAP) and Contention Free Period (CFP). Any device must use CSMA/CA to communicate during CAP. Guaranteed Time Slot (GTS) mechanism is used for CFP. During the inactive period, the coordinator does not interact with the network and goes to power saving mode.

- **Synchronizing to the beacons**

  A device attached to a coordinator, operating in a beacon enabled mode, can track the beacons to synchronize with the coordinator. This synchronization is important for data polling, energy saving, and detection of orphans.

  Upper layer may direct MAC to keep a track of the beacons for which the device will have to listen to every beacon sent by the coordinator to maintain synchronization.

- **Supporting Personal Area Network (PAN) association and disassociation**

  To support self configuration, 802.15.4 embeds association and disassociation functions in its MAC layer. This not only enables a star to be setup automatically, but also allows for the creation of a self-configuring, peer-to-peer network.

  A coordinator may indicate presence of a PAN by sending periodic beacons. The devices wishing to attach to the PAN listen to these beacons to extract necessary information to connect to the PAN. The device can associate to a PAN after performing a scan which gives the list of available PAN ids to upper layer (SSCS).

  An unassociated device sends an association request to the selected PAN's coordinator. The PAN coordinator sends back a response depending on availability of resources, using indirect transmission.

  Disassociation can be initiated either by the PAN coordinator or the device itself. Disassociation is always considered successful.

- **Employing Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism for channel access**

  Like most other protocols designed for wireless networks, 802.15.4 uses CSMA-CA mechanism for channel access. However, the new standard does not include the Request-To-Send (RTS) and Clear-To-Send (CTS) mechanism, considering the low data rate used in LR-WPANs.

  Devices will use slotted or unslotted CSMA-CA depending on the PAN is beacon-enabled or not, respectively. In slotted CSMA-CA channel access mechanism, the backoff period boundaries of every device in the PAN are aligned with the superframe slot boundaries of the PAN coordinator.

  Each device has 3 variables: NB, CW and BE. NB is the number of times the CSMA-CA algorithm was required to backoff while attempting the current transmission. It is initialized to 0 before every new transmission. CW is the contention window length, which defines the number of backoff periods that need to be clear of activity before the transmission can start. It is initialized to 2 before each transmission attempt and reset to 2 each time the channel is assessed to be busy. CW is only used for slotted CSMA-CA. BE is the backoff exponent, which is related to how many backoff periods a device should wait before attempting to assess the channel. The MAC layer will delay for a random number of complete backoff periods in the range 0 to 2BE - 1. Depending on the backoff periods, it senses channels for CW free slots. If it finds the channel free, it can send the data else it performs a random backoff again up to maximum of NB times.

- **Providing a reliable link between two peer MAC entities**

  The MAC layer employs various mechanisms to enhance the reliability of the link between two peers, among them are the frame acknowledgment and retransmission, data verification by using a 16-bit CRC, as well as CSMA-CA.

  MAC maintains a sequence number for transmitting a data frame. Similarly, another sequence number is maintained for sending beacon frames. A device can request for an acknowledgment by setting acknowledgment request field to 1 in the frame. The receiver should send the acknowledgment using the same sequence number as present in the original frame.

  Upon reception of packets, the MAC sublayer should discard all its received frames containing incorrect CRC values in their FCS field in the MFR.

- **Handling and maintaining GTS mechanism**

  In a beacon enabled mode, a PAN coordinator can allocate portions of the active superframe to a device. These portions are called GTSs, and comprise the contention free period (CFP) of the superframe.

  A GTS should be allocated only by the PAN coordinator and it should be used only for communications between the PAN coordinator and a device. A single GTS can extend over one or more superframe slots. The PAN coordinator may allocate up to seven GTSs at the same time. The GTS direction is specified as either transmit or receive. A GTS descriptor is specified in the beacon on successful allocation of a GTS.

- **Direct data transmission**

  Direct data transmission transfers data from a device to a coordinator. Unslotted CSMA-CA or slotted CSMA-CA is used for data transmission, depending whether non-beacon enabled mode or beacon enabled mode is used.

- **Indirect data transmission**

  Indirect data transmission transfers data from a coordinator to its devices. In this mode, a data frame is kept in a transaction list by the coordinator, then waits for extraction by the corresponding device. A device can find out if it has a packet pending in the transaction list by checking the beacon frames received from its coordinator. Occasionally, indirect data transmission can also happen in non-beacon enabled mode. For example, during an association procedure, the coordinator keeps the association response frame in its transaction list and the device polls and extracts the association response frame. Unslotted CSMA-CA or slotted CSMA-CA is used in the data extraction procedure.

SSCS Layer

This is the interface between MAC 802.15.4 and upper layers. It provides a way to access all the MAC primitives, but it can also serve as a wrapper of those primitives for convenient operations. It is an implementation specific module and its function should be tailored to the requirements of specific applications.

A brief description for SSCS features is as follows:

- Starting PAN coordinator

  When starting a new PAN, a PAN coordinator must be present. Configurable options will be passed to MAC layer before starting the coordinator.
- Starting Device

  A device can be started as either a RFD or an FFD. An FFD by default becomes a coordinator. A coordinator, like PAN coordinator, might be beacon enabled or non-beacon enabled.
- Stopping Device

  This feature allows a device to be stopped at a given point of time.
- Starting and Stopping Beacon

  A coordinator can change itself from non-beacon mode to beacon mode or otherwise. It can also change beacon parameters, if originally in beacon mode.

3.1.2 Features and Assumptions

This section describes the implemented features, omitted features, assumptions and limitations of the ZigBee MAC model.

3.1.2.1 Implemented Features

- Generating network beacons if the device is a coordinator
- Synchronizing to network beacons
- Supporting PAN association and disassociation
- Employing the CSMA-CA mechanism for channel access
- Direct and indirect data transmission
- Handling and maintaining the Guranteed Time Slot (GTS) mechanism
- Providing a reliable link between two peer MAC entities
- SSCS features, i.e., starting/stopping devices
- Data acknowledgement

3.1.2.2 Omitted Features

- Security
- Multiple interface support
- Starting and stopping beacon
- Disassociation mechanism

3.1.2.3 Assumptions and Limitations

- AODV must be used as the routing protocol
- The GTS mechanism works only if ZigBee Application is used as the Application Layer model. See Section 4.1 for details of the ZigBee Application model.

3.1.3 Supplemental Information

- None.

3.1.4 Command Line Configuration

To specify ZigBee MAC as the MAC protocol, include the following parameter in the scenario configuration (.config) file:

```
[<Qualifier>]  MAC-PROTOCOL   MAC802.15.4
```

The scope of this parameter declaration can be Global, Node, Subnet, or Interface. See Section 1.3.1.1 for a description of `<Qualifier>` for each scope.

Configuration Requirements

To use ZigBee MAC as the MAC protocol, the PHY protocol must be configured to be ZigBee PHY. See Section 2.1 for details of configuring ZigBee PHY.

ZigBee MAC Parameters

Table 3-1 lists the ZigBee MAC parameters specified in the scenario configuration (.config) file. See Section 1.3.1.3 for a description of the format used for the parameter table.

TABLE 3-1. ZigBee MAC Parameters

Parameter	Value	Description
MAC-802.15.4-DEVICE-TYPE *Optional* *Scope:* All	List: • FFD • RFD *Default:* RFD	Specifies the type of device assigned to a node. If MAC-802.15.4-DEVICE-TYPE is set to FFD, then configure the following parameter: • MAC-802.15.4-FFD-MODE. If MAC-802.15.4-DEVICE-TYPE, is set to RFD, then configure the following parameter: • MAC-802.15.4-POLL-INTERVAL
MAC-802.15.4-FFD-MODE *Optional* *Scope:* All	List: • PANCOORD • COORD • DEVICE *Default:* PANCOORD	Specifies the FFD mode. If MAC-802.15.4-FFD-MODE is set to PANCOORD, then configure the following parameter: • MAC-802.15.4-ENABLE-GTS If MAC-802.15.4-FFD-MODE is set to a value other than PANCOORD, then configure the following parameter: • MAC-802.15.4-POLL-INTERVAL **Note:** This parameter is applicable only if MAC-802.15.4-DEVICE-TYPE is set to FFD.

TABLE 3-1. ZigBee MAC Parameters (Continued)

Parameter	Value	Description
`MAC-802.15.4-ENABLE-GTS` *Optional* *Scope:* All	List: • `YES` • `NO` *Default:* `NO`	Specifies whether or not the GTS mechanism is enabled. If `MAC-802.15.4-ENABLE-GTS` is set to `YES`, then configure the following parameter: • `MAC-802.15.4-GTS-TRIGGER-PRECEDENCE` **Note:** This parameter is applicable only if `MAC-802.15.4-FFD-MODE` is set to `PANCOORD`.
`MAC-802.15.4-GTS-TRIGGER-PRECEDENCE` *Optional* *Scope:* All	Integer *Range:* `[0, 7]` *Default:* `1`	Specifies the threshold precedence of a data packet above which the packet is eligible for GTS transmission. **Note:** This parameter is applicable only if `MAC-802.15.4-ENABLE-GTS` is set to `YES`.
`MAC-802.15.4-ENABLE-DATA-ACKS` *Optional* *Scope:* All	List: • `YES` • `NO` *Default:* `NO`	Specifies whether or not acknowledegemnts are used during data transfer.
`MAC-802.15.4-COORD-BO` *Optional* *Scope:* All	Integer *Range:* `[0, 15]` *Default:* `3`	Specifies the beacon order for a (PAN) coordinator.
`MAC-802.15.4-COORD-SO` *Optional* *Scope:* All	Integer *Range:* `[0, 15]` *Default:* `3`	Specifies the superframe order for a (PAN) coordinator.
`MAC-802.15.4-START-DEVICE-AT` *Optional* *Scope:* All	Time *Range:* ≥ `0S`	Specifies the time to start a device.
`MAC-802.15.4-STOP-DEVICE-AT` *Optional* *Scope:* All	Time *Range:* ≥ `0S` *Default:* `0S`	Specifies the time at which the device will stop. If the stop time is set to `0S`, the device will remain on from the start time till the end of simulation.

TABLE 3-1. ZigBee MAC Parameters (Continued)

Parameter	Value	Description
`MAC-802.15.4-POLL-INTERVAL` *Optional* *Scope:* All	Time *Range:* `> 0S` *Default:* `1S`	Specifies the polling time used by a device to check for pending data in non-beacon enabled scenarios. **Note:** This parameter is applicable only if `MAC-802.15.4-DEVICE-TYPE` is set to `RFD` or `MAC-802.15.4-FFD-MODE` is set to `COORD` or `DEVICE`.
`MAC-LAYER-STATISTICS` *Optional* *Scope:* All	List: • `YES` • `NO` *Default:* `NO`	Indicates whether statistics are collected for MAC protocols, including ZigBee MAC.

3.1.5 GUI Configuration

This section describes how to configure ZigBee MAC model in the GUI.

Configuration Requirements

To use ZigBee MAC as the MAC protocol, the PHY protocol must be configured to be ZigBee PHY. See Section 2.1 for details of configuring ZigBee PHY.

Configuring ZigBee MAC Model Parameters

To configure the general ZigBee MAC parameters, perform the following steps:

1. Go to one of the following locations:
    - To set properties at subnet level, go to **Wireless Subnet Properties Editor > MAC Layer**.
    - To set properties at the interface level, go to one of the following locations:
        - **Interface Properties Editor > Interfaces > Interface # > MAC Layer**.
        - **Default Device Properties Editor > Interfaces > Interface # > MAC Layer**.

    In this section, we show how to configure ZigBee MAC Parameters in the Default Device Properties Editor for a specific interface. Parameters can be set in the other properties editors in a similar way.

2. Set **MAC Protocol** to *802.15.4* and set the dependent parameters listed in Table 3-2.

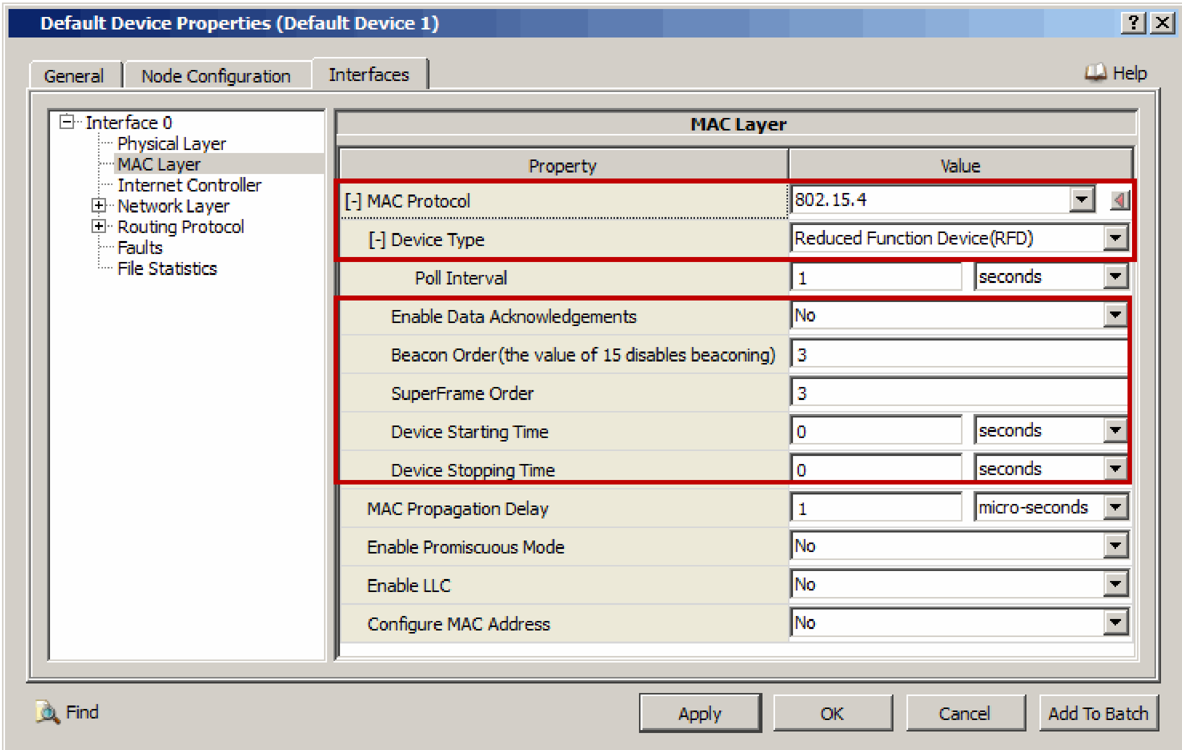

FIGURE 3-1. Selecting 802.15.4 MAC as MAC Protocol

TABLE 3-2. Command Line Equivalent of 802.15.4 MAC Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Device Type	Subnet, Interface	`MAC-802.15.4-DEVICE-TYPE`
Enable Data Acknowledgements	Subnet, Interface	`MAC-802.15.4-ENABLE-DATA-ACKS`
Beacon Order	Subnet, Interface	`MAC-802.15.4-COORD-BO`
SuperFrame Order	Subnet, Interface	`MAC-802.15.4-COORD-SO`
Device Starting Time	Subnet, Interface	`MAC-802.15.4-START-DEVICE-AT`
Device Stopping Time	Subnet, Interface	`MAC-802.15.4-STOP-DEVICE-AT`

Setting Parameters

- To enable RFD Device type, set **Device Type** to *Reduced Function Device(RFD),* otherwise, set **Device Type** to *Full Function Device(FFD).*

3. If **Device Type** is set to *Reduced Function Device (RFD)*, set the dependent parameters listed in Table 3-3.

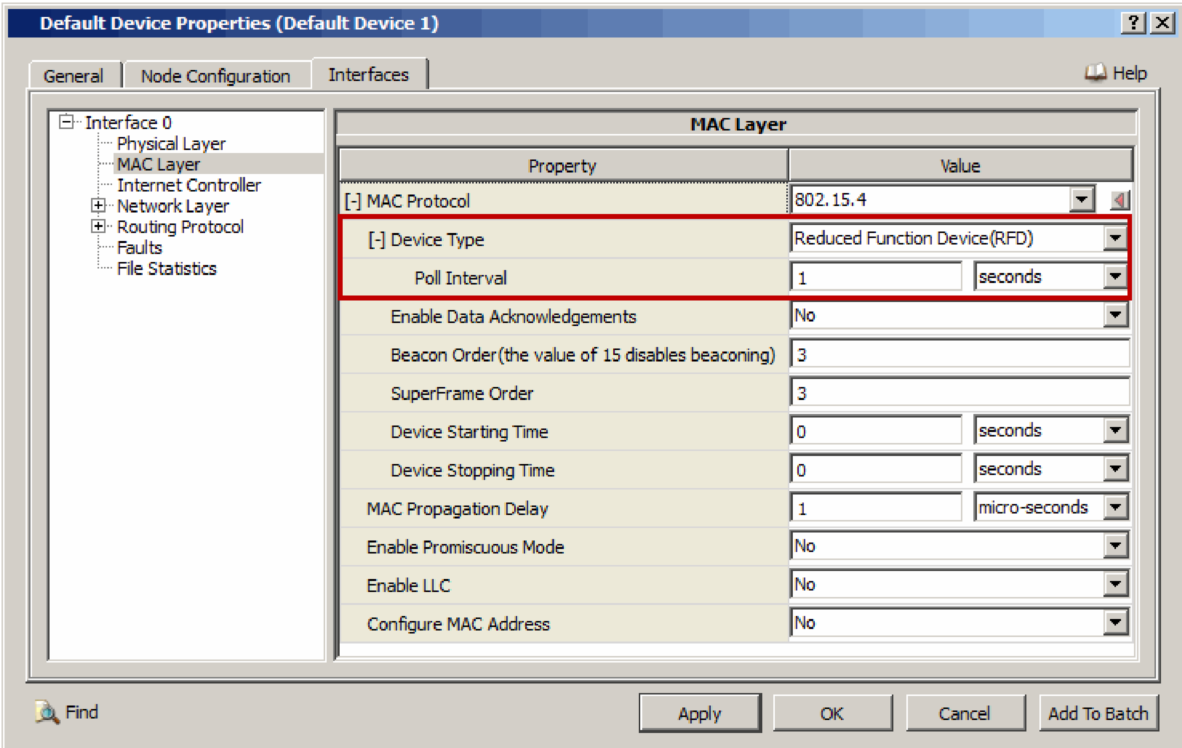

FIGURE 3-2. Configuring RFD Device Parameters

TABLE 3-3. Command Line Equivalent of RFD Device Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Poll Interval	Subnet, Interface	`MAC-802.15.4-POLL-INTERVAL`

4. If **Device Type** is set to *Full Function Device(FFD)*, set the dependent parameters as listed in Table 3-4.

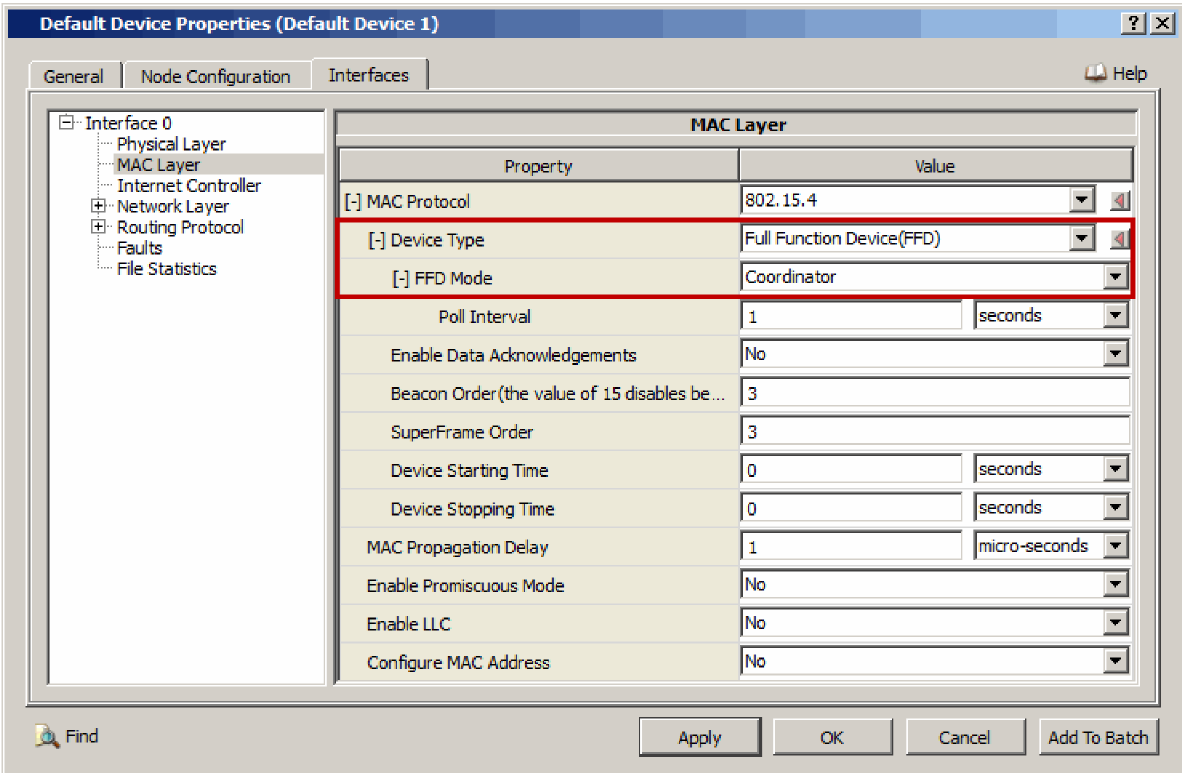

FIGURE 3-3. Configuring FFD Device Parameters

TABLE 3-4. Command Line Equivalent of FFD Device Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
FFD Mode	Subnet, Interface	`MAC-802.15.4-FFD-MODE`

5. If **FFD Mode** is set to *Device* or *Coordinator*, set the dependent parameters listed in Table 3-5.

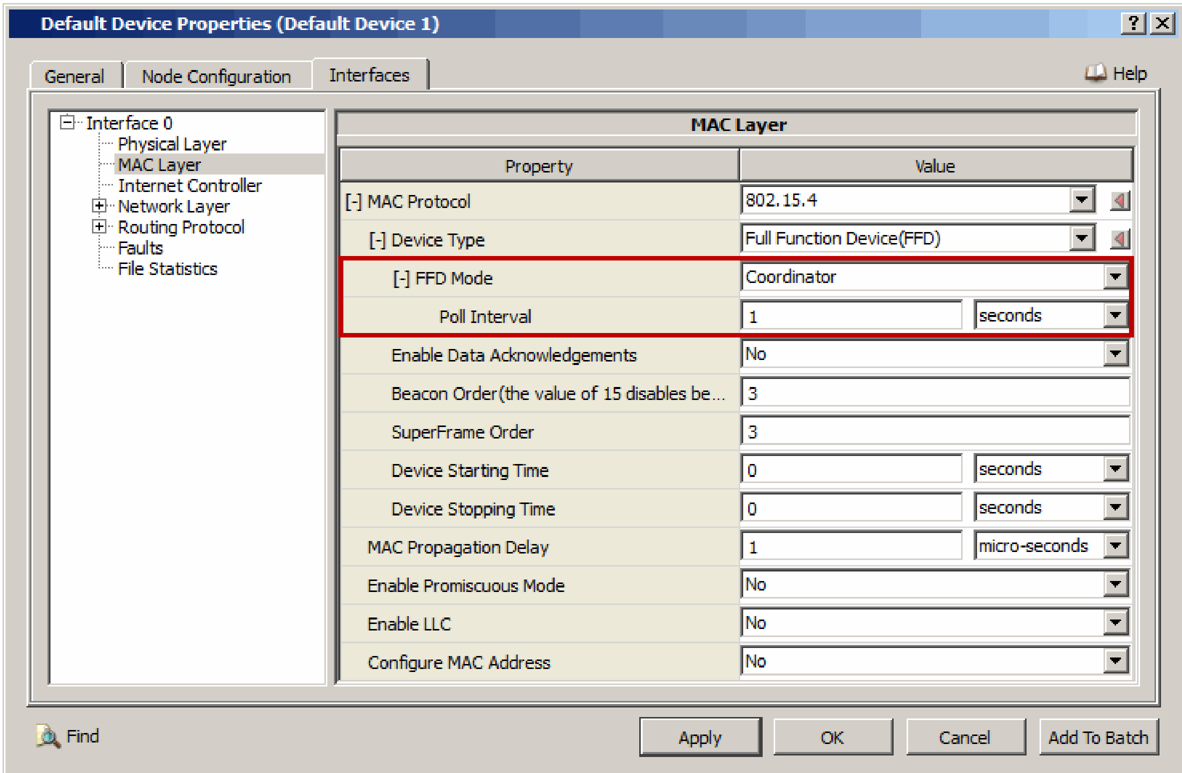

FIGURE 3-4. Configuring Device and Coordinator Parameters

TABLE 3-5. Command Line Equivalent of Device and Coordinator Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Poll Interval	Subnet, Interface	`MAC-802.15.4-POLL-INTERVAL`

6. If **FFD Mode** is set to *PAN Coordinator*, set the dependent parameters listed in Table 3-6.

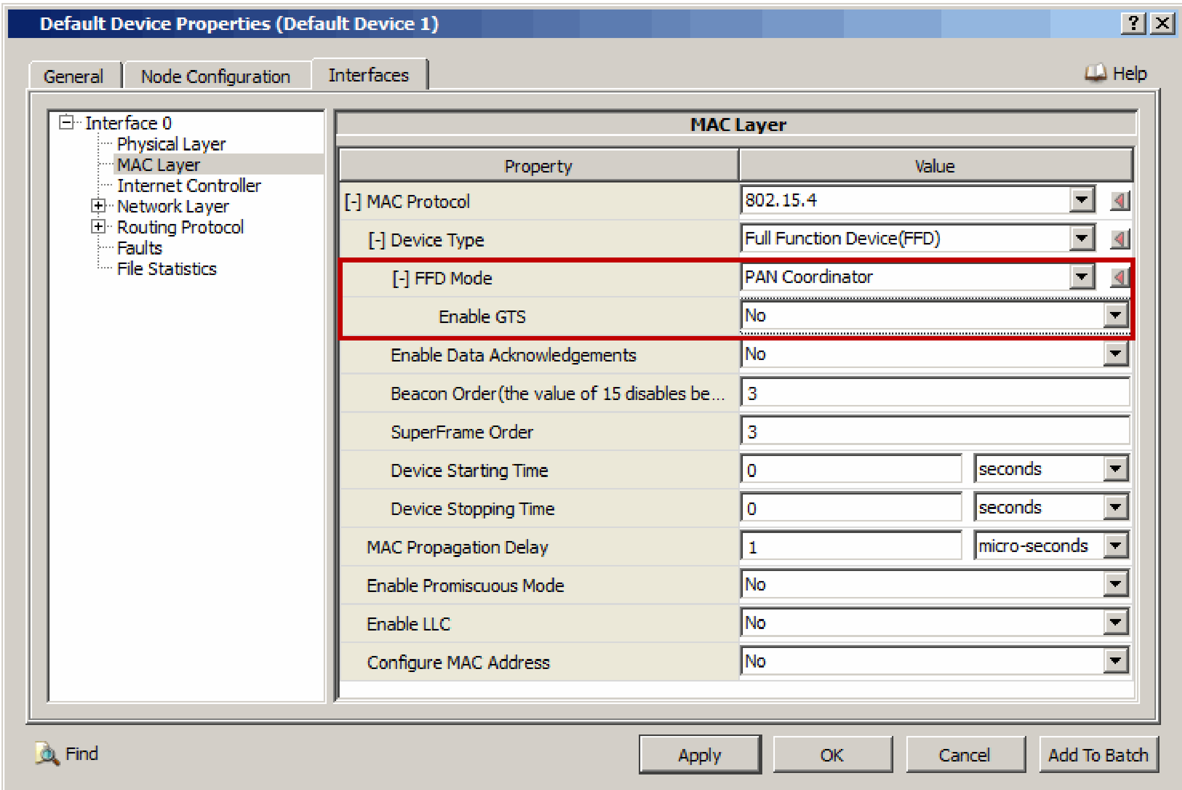

FIGURE 3-5. Configuring PAN Coordinator Parameters

TABLE 3-6. Command Line Equivalent of PAN Coordinator Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Enable GTS	Subnet, Interface	`MAC-802.15.4-ENABLE-GTS`

7. If **Enable GTS** is set to *Yes*, set the dependent parameters listed in Table 3-7.

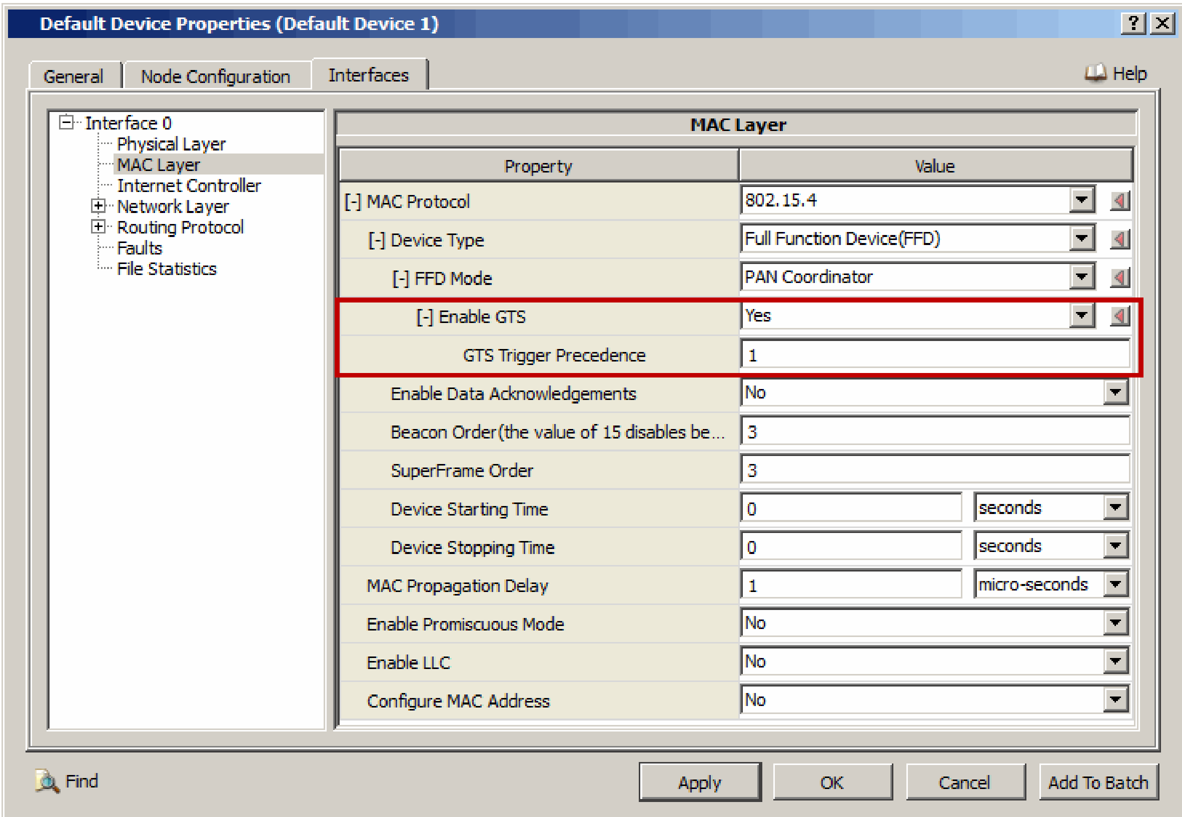

FIGURE 3-6. Configuring GTS Parameters

TABLE 3-7. Command Line Equivalent of GTS Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Enable GTS	Subnet, Interface	`MAC-802.15.4-ENABLE-GTS`

Configuring Statistics Parameters

Statistics for ZigBee MAC can be collected at the global, node, subent, and interface levels. See Section 4.2.9 of *QualNet User's Guide* for details of configuring statistics parameters.

To enable statistics collection for MAC protocols including ZigBee MAC, check the box labeled **MAC** in the appropriate properties editor.

TABLE 3-8. Command Line Equivalent of Statistics Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
MAC	Global, Node, Subnet, Interface	`MAC-LAYER-STATISTICS`

3.1.6 Statistics

Table 3-9 lists the statistics collected for the ZigBee MAC model that are output to the statistics (.stat) file at the end of simulation.

TABLE 3-9. ZigBee MAC Layer Statistics

Statistic	Explanation
Number Of Data Packets Queued For CAP	Total number of data packets queued in the CAP queues.
Number Of Data Packets De-Queued For CAP	Total number of data packets de-queued from the CAP queues.
Number Of Data Packets Sent In CAP	Total number of data packets sent in CAP
Number Of Data Packets Received	Total number of data packets received
Number Of Data Requests Sent	Total number of data requests command sent
Number Of Data Requests Received	Total number of data requests command received
Number Of Ack Sent	Total number of ack sent
Number Of Ack Received	Total number of ack received
Number Of Associate Requests Sent	Total number of associate requests command sent
Number Of Associate Requests Received	Total number of associate requests received
Number of Associate Response Sent	Total number of associate response sent
Number Of Associate Response Received	Total number of associate response received
Number Of Disassociate Requests Sent	Total number of disassociate request sent
Number Of Disassociate Requests Received	Total number of disassociate request received
Number Of Beacons Sent	Total number of beacons sent
Number Of Beacons Received	Total number of beacons received
Number Of Beacon Request Sent	Total number of beacon request commands sent
Number Of Beacon Request Received	Total number of beacon request commands received
Number Of Packets Dropped	Total number of packets dropped at MAC
Number Of Times Data Packets Retried Due To No Ack	Total number of times data packets retried due to no Ack
Number Of Data Packets Dropped Due To No Ack	Total number of data packets dropped due to no Ack
Number Of Data Packets Dropped Due To Channel Access Failure	Total number of data packets dropped due to channel access failure

TABLE 3-9. ZigBee MAC Layer Statistics (Continued)

Statistic	Explanation
GTS Feature Statistics	
Number Of Data Packets Queued For GTS	Total number of data packets queued in the GTS queues
Number Of Data Packets De-Queued For GTS	Total number of data packets de-queued from the GTS queue
Number Of Data Packets Sent In GTS	Total number of data packets sent in GTS
Number Of GTS Allocation Requests Received	Total number GTS allocation requests received
Number Of GTS De-Allocation Requests Received	Total number of GTS de-allocation requests received
Number Of GTS Requests Ignored	Total number of GTS requests ignored by Pan-coordinator due to various reasons
Number Of GTS Requests Rejected	Total number of GTS requests rejected by Pan-coordinator due to various reasons
Number Of GTS Expired	Total number of GTS expired
Number Of GTS Allocation Requests Sent	Total number of GTS allocation requests sent
Number Of GTS De-allocation Requests Sent	Total number of GTS de- allocation requests sent
Number Of GTS Requests Retried	Total number of GTS requests retried
Number Of GTS Requests Rejected By PanCoord	Total number of GTS request rejected by Pan-Coordinator (at a device)
Number Of GTS Allocation Requests Confirmed By PanCoord	Total number of GTS allocation request confirmed by Pan-Coordinator
SSCS LayerStatistics	
Number of Association requests accepted	Total number of association requests accepted
Number of Association requests rejected	Total number of association requests rejected
Number of Sync Loss reported	Total number of Synchronization Loss reported

3.1.7 Sample Scenarios

3.1.7.1 ZigBee Sample Scenario

The ZigBee sample scenario described in Section 2.1 illustrates the functionality of both ZigBee PHY and ZigBee Mac. See Section 2.1.7 for details.

3.1.7.2 GTS Sample Scenario

3.1.7.2.1 Sceanrio Description

In this section we setup a simple scenario consisting of five nodes. All the nodes are on one wireless subnet (default subnet). Node 1 is the PAN coordinator. All other nodes are coordinators. ZigBee applicationis configured from node 3 (Coordinator 2) to node 2 (Coordinator 1) and from node 5 (Coordinator 4) to node 4 (Coordinator 3). The scenario demonstrates the GTS allocation and de-allocation mechanism.

Topology

Figure 3-7 shows the topology of the sample scenario.

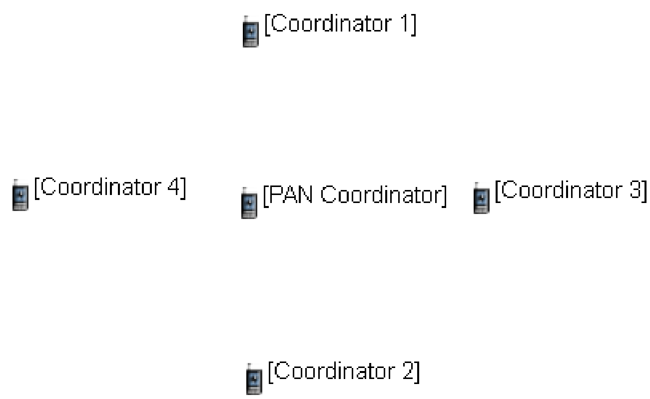

FIGURE 3-7. GTS Sample Scenario Topology

3.1.7.2.2 Command Line Configuration

Scenario Configuration File

1. Enable ZigBee MAC and ZigBee PHY at nodes 1 to 5.

```
[ 1 2 3 4 5 ] MAC-PROTOCOL   MAC802.15.4
[ 1 2 3 4 5 ] PHY-MODEL      PHY802.15.4
```

2. Set reception model, transmit power, modulation type, and channel assessment method for nodes 1 to 5.

```
[ 1 2 3 4 5 ] PHY802.15.4-TX-POWER     0.0
[ 1 2 3 4 5 ] PHY-RX-MODEL             PHY802.15.4
[ 1 2 3 4 5 ] PHY802.15.4-MODULATION   O-QPSK
[ 1 2 3 4 5 ] PHY802.15.4-CCA-MODE     CARRIER-SENSE
```

3. Set device type for nodes 1 to 5 to FFD. For node 1, set FFD Mode to PAN Coordinator and for nodes 2 to 5, set FFD Mode to Coordinator.

```
[ 1 2 3 4 5 ] MAC-802.15.4-DEVICE-TYPE FFD
[ 1 ] MAC-802.15.4-FFD-MODE PANCOORD
[ 2 3 4 5 ] MAC-802.15.4-FFD-MODE COORD
```

4. Set poll interval for nodes 2 to 5

```
[ 2 3 4 5 ] MAC-802.15.4-POLL-INTERVAL 1S
```

5. Set GTS parameters for PAN Coordinator (node 1).

```
[ 1 ] MAC-802.15.4-ENABLE-GTS   YES
[ 1 ] MAC-802.15.4-GTS-TRIGGER-PRECEDENCE  2
```

6. Set acknowledgement parameters.

```
[ 1 2 3 4 5 ] MAC-802.15.4-ENABLE-DATA-ACKS YES
```

7. Set beacon parameters.

```
[ 1 ] MAC-802.15.4-COORD-SO  3
[ 1 ] MAC-802.15.4-COORD-BO  3
[ 2 3 4 5 ] MAC-802.15.4-COORD-SO  15
[ 2 3 4 5 ] MAC-802.15.4-COORD-BO  15
```

8. Set device start/stop parameters.

```
[ 1 2 3 4 5 ] MAC-802.15.4-START-DEVICE-AT 0S
[ 1 2 3 4 5 ] MAC-802.15.4-STOP-DEVICE-AT 0S
```

9. Set routing parameters.

```
[ 1 2 3 4 5 ] ROUTING-PROTOCOL NONE
[ 1 2 3 4 5 ] STATIC-ROUTE YES
[ 1 2 3 4 5 ] STATIC-ROUTE-FILE ./gts_sample.routes-static
```

10. Enable statistics collection.

```
[ 1 2 3 4 5 ] PHY-LAYER-STATISTICS   YES
[ 1 2 3 4 5 ] MAC-LAYER-STATISTICS   YES
```

11. Specify application configuration file.

```
APPL-CONFIG-FILE   ./gts_sample.app
```

Application Configuration File (file gts_sample.app)

```
ZIGBEEAPP 3 2 100 70 1S 10S 0S PRECEDENCE 5
ZIGBEEAPP 5 4 100 70 0.25S 10S 0S PRECEDENCE 7
```

Static Routes File (file gts_sample.routes-static)

```
5   169.0.0.4  169.0.0.1
1   169.0.0.4  169.0.0.4
3   169.0.0.2  169.0.0.1
1   169.0.0.2  169.0.0.2
```

3.1.7.2.3 GUI Configuration

To configure the sample scenario in QualNet GUI, perform the following steps:

1. Place five nodes of the default device type on the canvas. (The nodes are connected to the default wireless subnet.)
2. To configure ZigBee PHY at nodes 1 to 5, do the following:
   a. Go to the **Default Device Properties Editor > Interfaces > Interface # > Physical Layer**.

- **b.** Set **Radio Type** to *802.15.4 Radio* (see Figure 3-8).
- **c.** Set **Transmission Power** to *0.0*.
- **d.** Set **Packet Reception Model** to *PHY802.15.4 Reception Model*.
- **e.** Set **Modulation Scheme** to *O-QPSK*.
- **f.** Set **CCA Mode** to *Carrier Sense*.

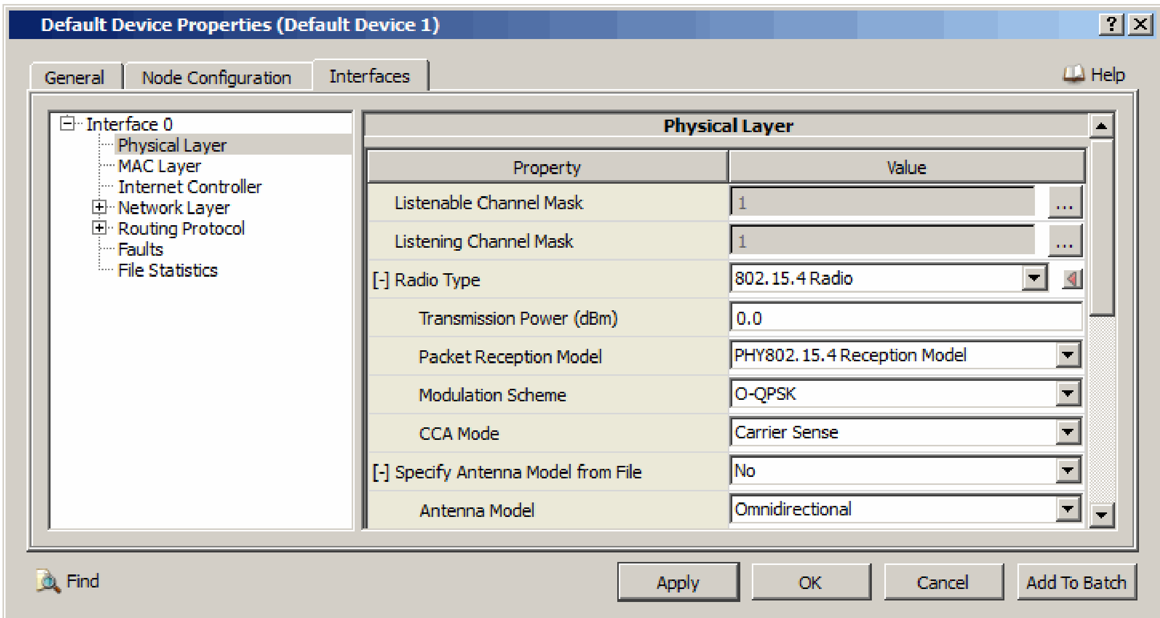

FIGURE 3-8. Setting Radio Parameters

3. To configure ZigBee MAC at node 1, do the following:

- **a.** Go to the **Default Device Properties Editor > Interfaces > Interface # > MAC Layer**.
- **b.** Set **MAC Protocol** to *802.15.4* (see Figure 3-9).
- **c.** Set **Device Type** to *Full Function Device (FFD)*.
- **d.** Set **FFD Mode** to *PAN Coordinator.*
- **e.** Set **Enable GTS** to *Yes*.
- **f.** Set **GTS Trigger Precedence** to *2*.
- **g.** Set **Enale Data Acknowledgemnts** to *Yes*.
- **h.** Set **Beacon Order** to *3*.
- **i.** Set **SuperFrame Order** to *3*.
- **j.** Set **Device Starting Time** to *0 second*.
- **k.** Set **Device Stopping Time** to *0 second*.

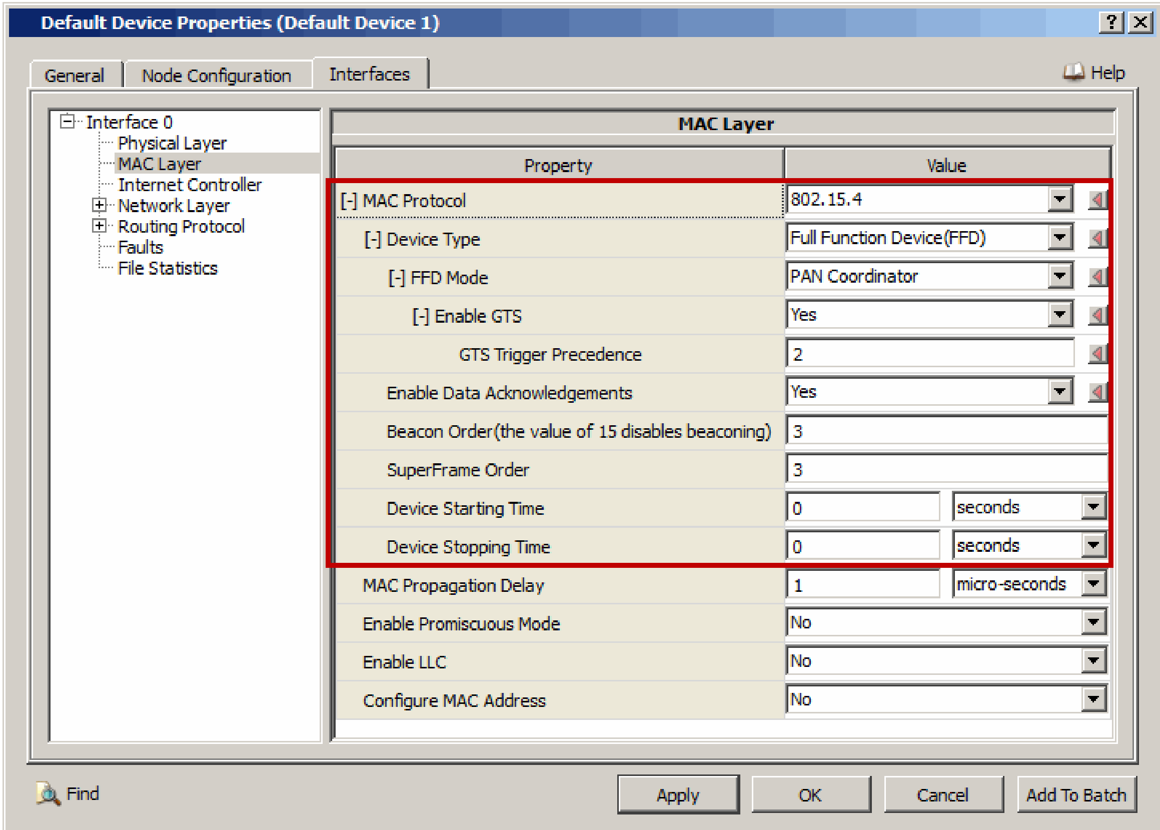

FIGURE 3-9. Setting MAC Protocol Parameters for Node 1

4. To configure ZigBee MAC at nodes 2 to 5, do the following:

a. Go to the **Default Device Properties Editor > Interfaces > Interface # > MAC Layer**.

b. Set **MAC Protocol** to *802.15.4* (see Figure 3-10).

c. Set **Device Type** to *Full Function Device (FFD)*.

d. Set **FFD Mode** to *Coordinator*.

e. Set **Poll Interval** to *1 second*.

f. Set **Enale Data Acknowledgemnts** to *Yes*.

g. Set **Beacon Order** to *15*.

h. Set **SuperFrame Order** to *15*.

i. Set **Device Starting Time** to *0 second*.

j. Set **Device Stopping Time** to *0 second*.

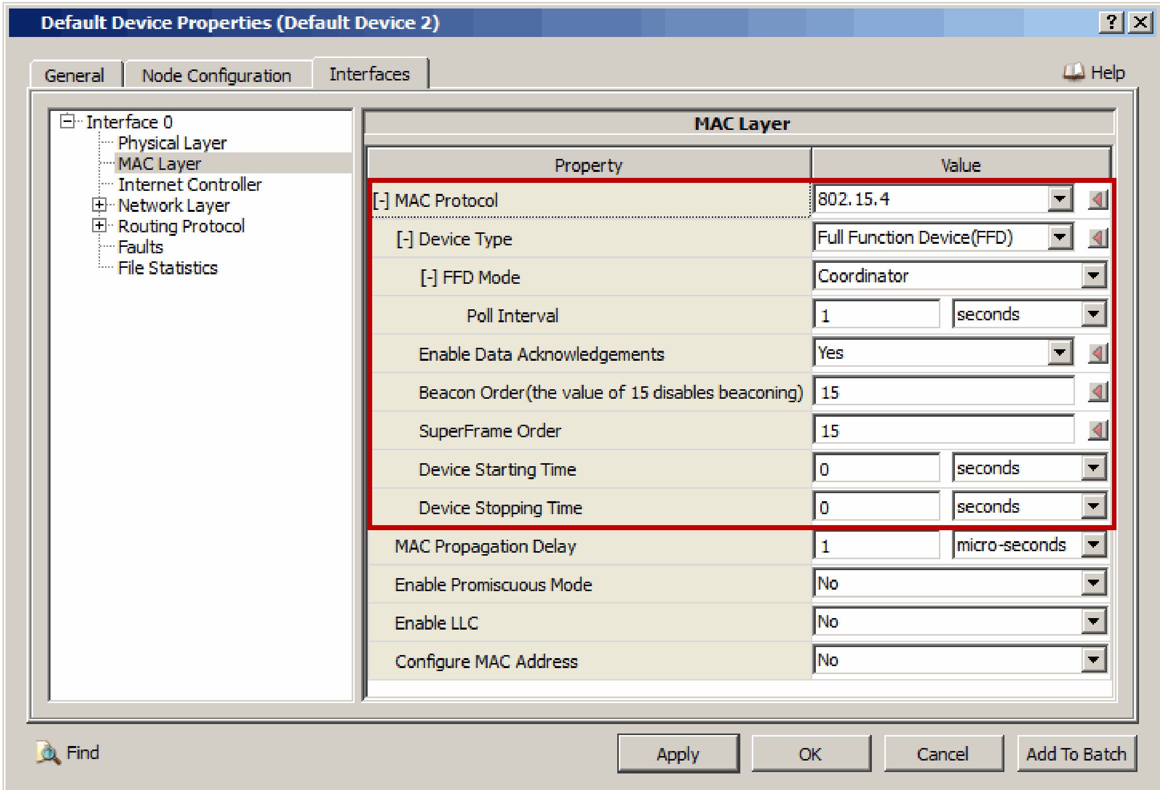

FIGURE 3-10. Setting MAC Protocol Parameters for Nodes 2 to 5

5. For nodes 1 to 5, go to **Default Device Properties Editor > Node Configuration > Routing Protocol**.
   a. Set **Routing Protocol IPv4** to *None*.
   b. Set **Specify Static Routes** to *Yes*.
   c. Set **Static Route File** to *gts_sample.routes-static*. (See Section 3.1.7.2.2 for the contents of the static route file.)
6. To enable statistics collection, go to **Scenario Properties Editor > Statistics and Tracing > File Statistics**. Check the **MAC** and **PHY/Radio** boxes.
7. Set up a ZigBee Application session from node 3 to node 2 (see Section 4.1 for details).
   a. Set **Items to Send** to *100*.
   b. Set **Item Size** to *70*.
   c. Set **Interval** to *1 second*.
   d. Set **Start Time** to *1 second*.
   e. Set **End Time** to *1 second*.
   f. Set **Precedence Value** to *5*.
8. Set up a ZigBee Application session from node 5 to node 4.
   a. Set **Items to Send** to *100*.
   b. Set **Item Size** to *70*.
   c. Set **Interval** to *0.25 second*.
   d. Set **Start Time** to *1 second*.

e. Set **End Time** to *1 second*.
f. Set **Precedence Value** to *7*.

3.1.8 Scenarios Included in QualNet

The QualNet distribution includes several sample scenarios for the ZigBee MAC model. All scenarios are located in the directory QUALNET_HOME/scenarios/sensor_networks. Table 3-10 lists the sub-directory where each scenario is located.

TABLE 3-10. ZigBee MAC Model Scenarios

Scenario Sub-directory	Description
Battlefield Monitoring with Sensors	
BattlefieldMonitoringwithSensors	Demonstrates data collection from ground sensors using mobile vehicles.
ZigBee	
2-node	Demonstrates beacon generation, association and direct data transfer.
multi-app-at-same-time	Demonstrates multiple applications configured between RFD and PAN-Coordinator.
multiple-ffd	Demonstrates the behavior FFD, i.e., beacon generation and association with RFD.
nonbeacon-enable	Demonstrates the communication between devices in nonbeacon enabled mode.
orphaned-device	Demonstrates the behavior of a mobile device which is transmitting data packets and becomes disassociated (orphaned) from the PAN coordinator.
ZigBee Auto Home	
ZigBee-AutoHome	Demonstrates an application of ZigBee technology for Home Automation. It demonstrates the monitoring and control capability that can be achieved with ZigBee.
ZigBee GTS Feature	
transmit-receive-gts	Demonstrates the transmit Guatranteed Time Slot (GTS) and receive GTS functionality.
transmit-gts-expiry	Demonstrates the transmit GTS expiration functionality.
receive-gts-expiry	Demonstrates the receive GTS expiration functionality.

3.1.9 References

1. LAN-MAN Standards Committee of the IEEE Computer Society, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE, 2006
2. LAN-MAN Standards Committee of the IEEE Computer Society, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE, 2003
3. Sinem Coleri Ergen, "ZigBee/IEEE 802.15.4 Summary", September 2004

4. http://ees2cy.engr.ccny.cuny.edu/zheng/pub/ - CCNY Electrical Engineering Department's ZigBee implementation in ns-2.

4 Application Layer Models

This chapter describes features, configuration requirements and parameters, statistics, and scenarios for Application Layer Models in the Sensor Networks Model Library, and consists of the following section:

- ZigBee Application

4.1 ZigBee Application

4.1.1 Description

The ZigBee Application generates traffic at a constant rate by transmitting packets (also called “items”) of a fixed size at a fixed rate. It is generally used to provide background traffic in a sensor network where devises use the Guaranteed Time Slot (GTS) mechanism for data transmission.

The ZigBee Application can be used to simulate applications for which the end-systems require predictable response time and a static amount of bandwidth is continuously available for the life-time of the connection.

4.1.2 Features and Assumptions

This section describes the implemented features, omitted features, assumptions and limitations of the ZigBee Application model.

4.1.2.1 Implemented Features

- Transmission of packets of a fixed size with a constant inter-packet time.

4.1.2.2 Omitted Features

None.

4.1.2.3 Assumptions and Limitations

- For the GTS feature to work, the value of `PRECEDENCE` (see Section 4.1.3) should be higher than the value configured for the MAC parameter `MAC-802.15.4-GTS-TRIGGER-PRECEDENCE` (see Section 3.1).

4.1.3 Command Line Configuration

Application Configuration File Parameters

To configure a ZigBee Application session, include the following statement in the application configuration (.app) file:

```
ZIGBEEAPP    <src> <dest> <items-to-send> <item-size> <interval>
             <start-time> <end-time> [PRECEDENCE <precedence-value>]
```

Note: All parameters should be entered on the same line.

The ZigBee Application parameters are described in Table 4-1. See Section 1.3.1.3 for a description of the format used for the parameter table.

TABLE 4-1. ZigBee Application Parameters

Parameter	Value	Description
`<src>` *Required*	Integer or IP Address	Client node's ID or IP address.
`<dest>` *Required*	Integer or IP Address	Server node's ID or IP address.
`<items-to-send>` *Required*	Integer *Range:* ≥ `0`	Number of packets to send. If this is set to `0`, items will be sent continually until `<end-time>` or until the end of the simulation, whichever comes first. See note.
`<item-size>` *Required*	Integer *Range:* `[32, 65023]` *Unit:* bytes	Size of each item.
`<interval>` *Required*	Time *Range:* `> 0S`	Time between transmission of successive packets (inter-departure time).
`<start-time>` *Required*	Time *Range:* ≥ `0S`	Time when the transmission of packets should begin.
`<end-time>` *Required*	Time *Range:* ≥ `0S`	Time when the transmission of packets should end. If this is set to `0`, transmission ends after `<items-to-send>` packets have been sent or until the end of simulation, whichever comes first. **Note:** `<end-time>` should be `0` or greater than `<start-time>`.
`PRECEDENCE <precedence-value>` *Optional*	Integer *Range:* `[0, 7]`	Value of the 3-bit Precedence field of the IP header for the packets generated. If `PRECEDENCE` is not specified, `PRECEDENCE 0` is used as default.

Note: If `<items-to-send>` and `<end-time>` are both greater than 0, packets are transmitted until `<items-to-send>` packets have been sent, `<end-time>` is reached, or the simulation ends, whichever comes first.

Scenario Configuration File Parameters

Table 4-2 describes the ZigBee Application parameters that can be specified in the scenario configuration (.config) file.

TABLE 4-2. ZigBee Application Scenario Configuration File Parameters

Parameter	Value	Description
`APPLICATION-STATISTICS` *Optional* *Scope:* Global, Node	List: • `YES` • `NO` *Default:* `NO`	Indicates whether statistics collection is enabled for applications (including ZigBee Application).
`TRACE-ZIGBEEAPP` *Optional* *Scope:* Global, Node	List: • `YES` • `NO` *Default:* `YES`	Indicates whether packet tracing is enabled for ZigBee Application. **Note:** To enable packet tracing, some other parameters need to be configured as well. Refer to Section 4.2.10 of *QualNet User's Guide* for details.

Examples of Parameter Usage

The following are examples of ZigBee Application configuration:

1. Node 1 sends to node 2 ten items of 1460 bytes each, starting at the beginning of the simulation and up to 600 seconds into the simulation. The inter-packet time is 3 seconds.

```
ZIGBEEAPP 1 2 10 1460 3S 0S 600S
```

2. Node 1 continually sends to node 2 items of 1460 bytes each, starting at the beginning of the simulation and ending at 600 seconds into the simulation. The inter-packet time is 1 second. The total number of items sent is 600.

```
ZIGBEEAPP 1 2 0 1460 1S 0S 600S
```

3. Node 1 continually sends to node 2 items of 1460 bytes each, starting at the beginning of the simulation. Packets are sent until the end of the simulation. The inter-packet time is 1 second.

```
ZIGBEEAPP 1 2 0 1460 1S 0S 0S
```

4. Node 1 sends to the node with IP address 192.168.0.8 10 items of 1460 bytes, starting at 5 seconds into the simulation and up to 600 seconds into the simulation. The inter-packet time is 1 second. The Precedence value for each packet is set to 5. The total number of items sent is 595.

```
ZIGBEEAPP 1 192.168.0.8 10 1460 1S 5S 600S PRECEDENCE 5
```

4.1.4 GUI Configuration

ZigBee Application is configured using the ZigBee Application Properties Editor.

To configure a ZigBee Application session between two nodes, perform the following steps:

1. Click the **ZIGBEE** button in the **Applications** tab of the Standard Toolset.
2. On the canvas, click on the source node, drag the mouse to the destination node, and release.
3. Open the ZigBee Application Properties Editor by doing one of the following:
   a. Right-click in the application link on the canvas and select **Properties** from the menu.
   b. In the **Applications** tab of Table View either double-click on the application row or right-click on the application row and select **Properties** from the menu.
4. Set the parameters listed in Table 4-3.

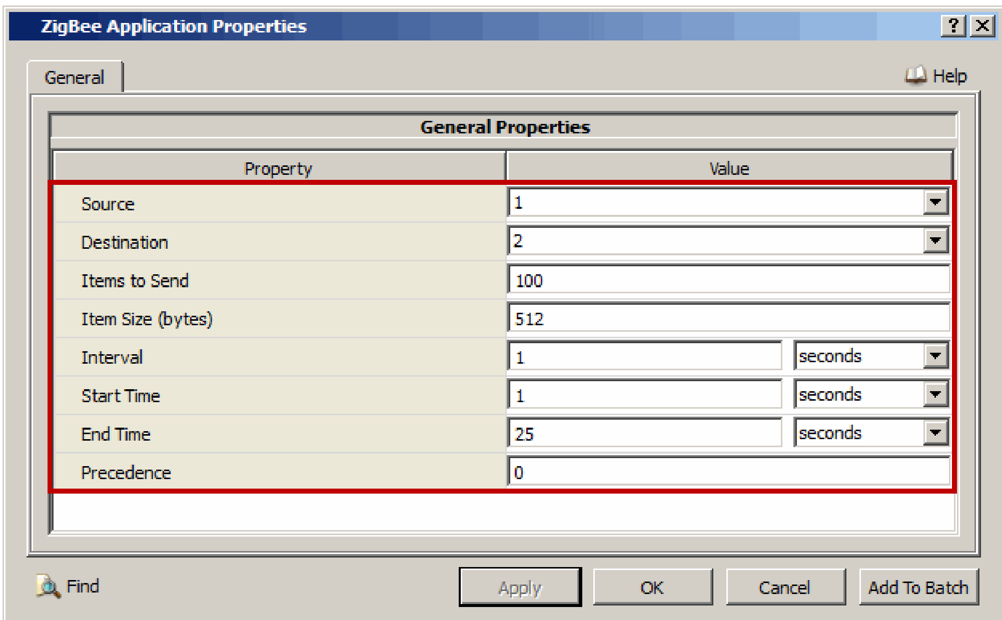

FIGURE 4-1. Setting ZigBee Application Parameters

TABLE 4-3. Command Line Equivalent of ZigBee Application Parameters

GUI Parameter	Command Line Parameter
Source	`<src>`
Destination	`<dest>`
Items to Send	`<items-to-send>`
Item Size	`<item-size>`
Start Time	`<start-time>`
End Time	`<end-time>`
Interval	`<interval>`
Precedence	`<precedence-value>`

Setting Parameters

- To specify an IP address as the source (destination) ID, set **Source** (**Destination**) to one of the IP addresses listed in the drop-down list.

Configuring Statistics Parameters

Statistics for applications (including ZigBee Application) can be collected at the global and node levels. See Section 4.2.9 of *QualNet User's Guide* for details of configuring statistics parameters.

To enable statistics collection for ZigBee Application, check the box labeled **Application** in the appropriate properties editor.

TABLE 4-4. Command Line Equivalent of Statistics Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Application	Global, Node	`APPLICATION-STATISTICS`

Configuring Packet Tracing Parameters

Packet tracing for ZigBee Application can be enabled at the global and node levels. To enable packet tracing for ZigBee Application, in addition to setting the ZigBee Application trace parameter, **Trace ZigBee Application**, several other trace parameters also need to be set. See Section 4.2.10 of *QualNet User's Guide* for details of configuring packet tracing parameters.

TABLE 4-5. Command Line Equivalent of Packet Tracing Parameters

GUI Parameter	Scope of GUI Parameter	Command Line Parameter
Trace ZigBee Application	Global, Node	`TRACE-ZIGBEEAPP`

4.1.5 Statistics

Table 4-6 lists the ZigBee Application statistics that are output to the statistics (.stat) file at the end of simulation.

TABLE 4-6. ZigBee Application Statistics

Statistic	Description
ZigBee Application Client Statistics	
Server address	Server address for ZigBee Application Client
First Packet Sent at (s)	Time when first packet was sent (seconds)
Last Packet Sent at (s)	Time when last packet was sent (seconds)
Session status	Status of the session (open or closed) at the end of simulation
Total Bytes Sent	Total number of bytes sent
Total Packets Sent	Total number of packets sent
Throughput (bits/s)	Throughput at the client (bits/second). See note 1.
ZigBee Application Server Statistics	
Client address	Address of the client

TABLE 4-6. ZigBee Application Statistics (Continued)

Statistic	Description
First packet received at (s)	Time when first packet was received (seconds)
Last packet received at (s)	Time when last packet was received (seconds)
Session status	Current status of the session
Total Bytes Received	Total number of bytes received
Total Packets Received	Total number of packets received
Throughput (bits/s)	Throughput at the server (bits/second). See note 2.
Average End-to-End Delay	Average delay for packet transmission between client and server (seconds). See note 3.
Average Jitter	Average jitter for packet transmission between client and server (seconds). See note 4.

Notes: **1.** The throughput at the client is calculated as follows:

- If the session is complete, i.e., if all packets have been sent before the simulation ends, throughput = (total bytes sent * 8) / (time last packet sent - time first packet sent), where the times are in seconds.
- If the session is incomplete, i.e., if all packets have not been sent before the simulation ends, throughput = (total bytes sent * 8) / (simulation time - time first packet sent), where the times are in seconds.

2. The throughput at the server is calculated as follows:

- If the session is complete, throughput = (total bytes received * 8) / (time last packet received - time first packet received), where the times are in seconds.
- If the session is incomplete, throughput = (total bytes received * 8) / (simulation time - time first packet received), where the times are in seconds.

3. Average end-to-end delay = (total of transmission delays of all received packets) / (number of packets received),
where,
transmission delay of a packet = time packet received at server - time packet transmitted at client, where the times are in seconds.

4. Average jitter = (total packet jitter for all received packets) / (number of packets received - 1)
where,
packet jitter = transmission delay of the current packet - transmission delay of the previous packet.
Jitter can be calculated only if at least two packets have been received.