CYGNUS SMARTNET WIRELESS FIRE ALARM

MESH PROTOCOL

SPECIFICATION

2001-SPC-0012-02

Document No:	**2001-SPC-0012**	**Client Ref:**			
Document revision history					
Rev	**Description**	**Date Approved**	**Author**	**Checked**	**Approved**
A20	Reviewed by AT	07-Feb-17	PW		
A21	Incorporated changes from AT review	08-Feb-17	PW		
A24	Incorporated PHY section from AT	15-Feb-17	PW		
A29	CYG2-298 changed from imm-ack to enh-ack	01-Mar-17	PW		
A35	Incorporated updated PHY and MAC parts from AT	15-Mar-17	PW		
A37	Version submitted for CDR	17-Mar-17	PW		
A38	Changes identified in CDR	19-Jul-17	PW		
A	Up-issued to release A	24-Jul-17	PW		
B1	Replaced dynamic power control with simple fixed power option following review comment	31-Jul-17	PW		
B2	Further changes identified by NM from CDR	09-Aug-17	PW		
B	Up-issued to release B – Agreed by NM. Contains all changes identified in CDR.	09-Aug-17	PW		
C1	Separated RACH and ACK into different slots in figure 7 and table 11	10-Oct-17	PW		
C2	Changed the MIC (message integrity check) field to the SystemId field.	31-Oct-17	AT		
C3	Removed the root address field from the heartbeat payload.	08-Nov-17	AT		
C4	Replaced Battery Level command parameter with Status Flags parameter.	28-Nov-17	PC		

C5	Changes made to describe mesh forming and healing. Reviewed by Peter Whitworth, and remedial changes added by Andy.	18-Dec-17	AT		
C6	Added description of test messages from Peter Connolly	20-Dec-17	PW		
C7	Update the Wired Firmware Update section	02-Jan-18	KM		
C8	Update Status Indication Message diagram.Updated Application message table.	10-Jan-18	PC		
C9	Removed duplicate table 21.	17-Jan-18	PW		
C10	Changed rank field from 5 to 6 bits in section 8.2.2. Note that the spreadsheet HKD-17-0065-D_B1 Mesh Protocol Message Lengths already had this field as 6 bits, so required no change.	15-Feb-18	AT		
C11	Updated Neighbour Information description. Changed from RSSI to SNR. Improved descriptions for Slot Index field in section 6.2.2.	15-Feb-18	PC		
C12	RBU Disable message added, and its parameter Unit Address defined.	16-Feb-18	AT		
C13	Transmission duration estimates updated in Table 5, and duty cycle calculations for various events in 1 hour period added in Section 5.10.2.	17-Feb-18	AT		
C14	Added new parameter types to Table 22 for SVI, RBU Disable, Low Tx Power and High Tx Power.	20-Mar-18	PC		
C15	Replaced AT command section with reference to SW architecture and design document	28-Mar-18	PW		
C16	Updated Figure 10: Link Failure Detection	03-Apr-18	AT		
C17	Corrections to packet descriptions in Sections 4.1 and Tables 5, 12 and 13. Slot structure descriptions and figures changed in Sections 6.2, 6.3 and 6.4.	04-Apr-18	AT		
C18	Changes following review by Nick M and Andy	11-Apr-18	PW		
C19	Changes following review by Nick M	16-Apr-18	PW		
C	Up-issued for release to Bull in final document pack	18-Apr-18	PW		
D1	Updates to Status Indication message and Fault Signal message	12-Jun-18	PC		
D2	Described time-separated DLCCH transmissions in section 6.	04-Jul-18	PC		
D3	Added Output Status Request message and Output Status message. Modified Route Add message.	24-Jul-18	PC		
D4	Updated Output State message to include all output profiles and programmed zone.	07-Aug-18	PC		
D5	Updated Parameters table and definitions in section 8.	20-Sep-18	PC		

Cygnus Smartnet Wireless Fire Alarm Mesh Protocol Specification

D6	Added Output Duration field to the Output Signal message. Added “IO Input 1 Fault” and “IO Input 2 Fault” to the Status flags field for the Status indication message.	08-Oct-18	PC		
D7	Removed ‘low link quality’ and ‘low number of parents’ from the Fault Status flags. Removed three unused output profiles (6,7,8) from the table.	25-Oct-18	PC		
D8	Changed threshold parameter commands to contain day and night threshold. Added new commands to parameter table, Mesh Status, Head LED, Plugin ID Number, Day/Night setting	07-May-19	PC		
01	Reformatted and renumbered from PA document HKD-16-0015-D	10-Nov-16	PC	AK	AK
01A	Simplified RU Channel Index Added device combination types	23-Apr-20	AK		
01B	Unnoted	5-Jun-20	AK		
01C	Underway revise throughout to reflect TDM structure change and other modification	22-Dec-20	DK		
02	Updated message formats	19 Aug 21	Peter Connolly PC Digitally signed by Peter Connolly Date: 2021.08.26 13:57:21 +01'00'	Alastair Knight Digitally signed by Alastair Knight Date: 2021.08.26 15:10:22 +01'00'	Giles Hemmings Digitally signed by Giles Hemmings Date: 2021.08.26 16:19:42 +01'00'

HARD COPIES ARE UNCONTROLLED

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

1.1 Purpose

This is the Mesh Protocol Design document for the Cygnus 2 project. It originated as a PA Consulting deliverable document provided to Cygnus Group Limited.

Cygnus 2 is a wireless fire detection system, the components of which conform to the EN54 standard. It includes multiple remote units that can be detectors or output devices (e.g. sounders or beacons) and a central NCU (Network Coordinator Unit) which connects to a Control Panel. Cygnus 2 is a mesh network. This document describes the protocol used for the mesh network.

The aim of the document is to describe the protocol in sufficient detail that it can be implemented in the Remote Units and on the NCU.

1.2 Ownership of this document

This document was commenced by PA Consulting for Cygnus Group Limited, though has since been updated by Cygnus Group. PAs document numbering system was used initially, though has now been supplanted by Cygnus Group numering system. The ownership of the document belongs to Cygnus Group.

1.3 Contractual status of document

This document is one of the deliverables for the Cygnus 2 project. It was initially written by PA for Cygnus Group Limited.

1.4 Relationship to other documents

The relationship between this document and other key project documents is shown in Figure 1.

The Devolved Radio Requirements [8] are derived from the System Requirements Specification [7].

This latter document contains a protocol designed to meet the Devolved Radio Requirements.

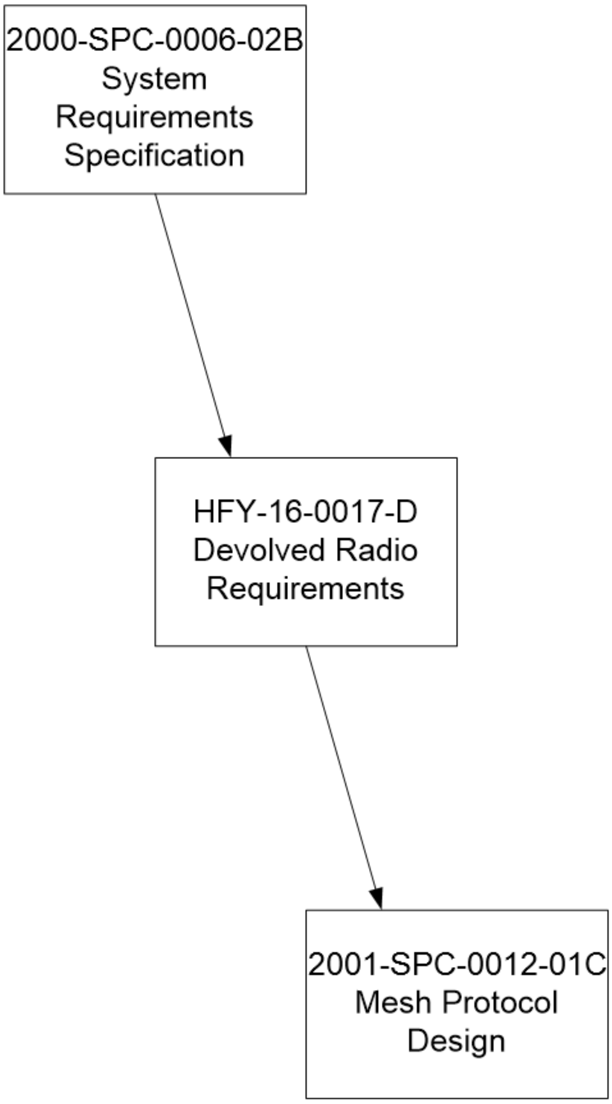


Figure 1: Document Relationship

1.5 System Architecture

The system architecture diagram below is based on that within the Cygnus 2 System Architecture Diagrams document [6]. An earlier version of the diagram was presented in the Phase 1b report [5] generated in the Taurus project that preceded this design.

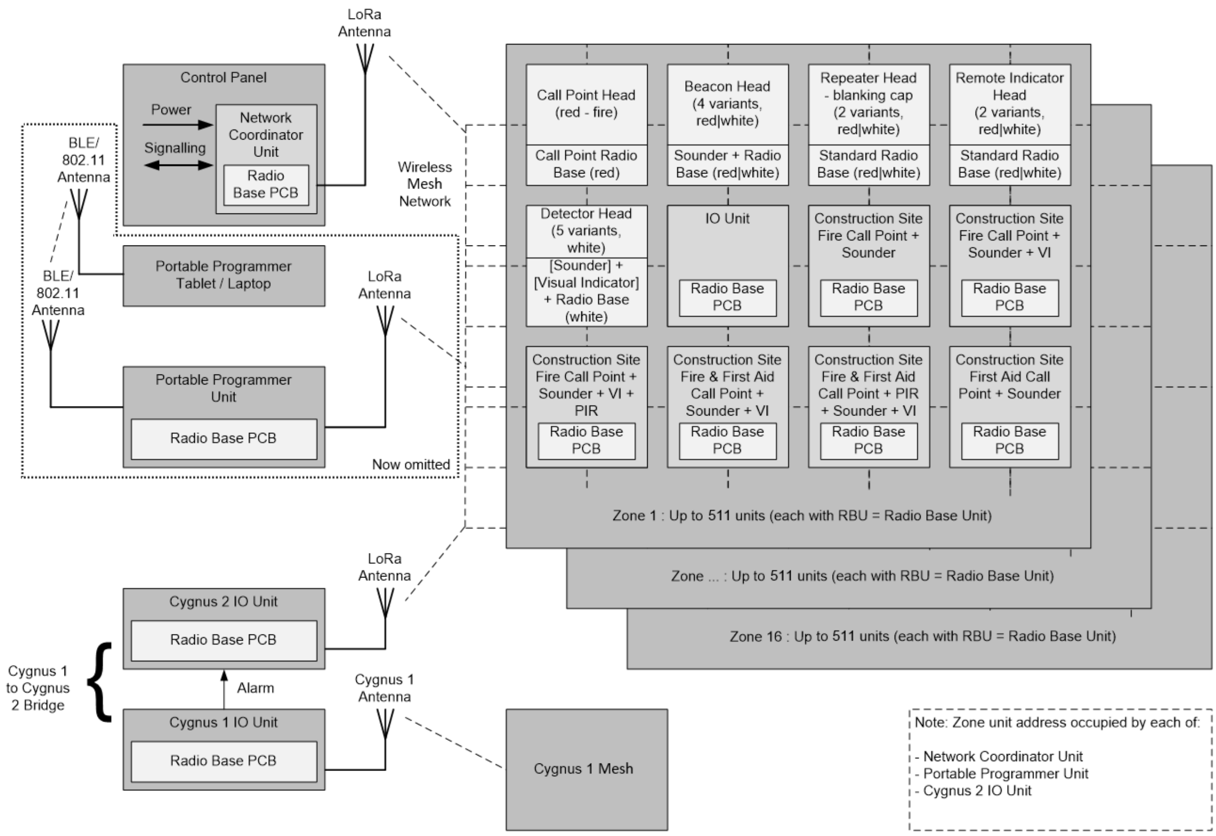


Figure 2: System Architecture

A system consists of a single control panel, a single Network Coordinator Unit and up to 511 remote units.

For a large scale implementation, up to 5 systems can be combined into a System-of-Systems. Each system will have its own Control Panel and Network Coordinator Unit.

1.6 Mesh Network

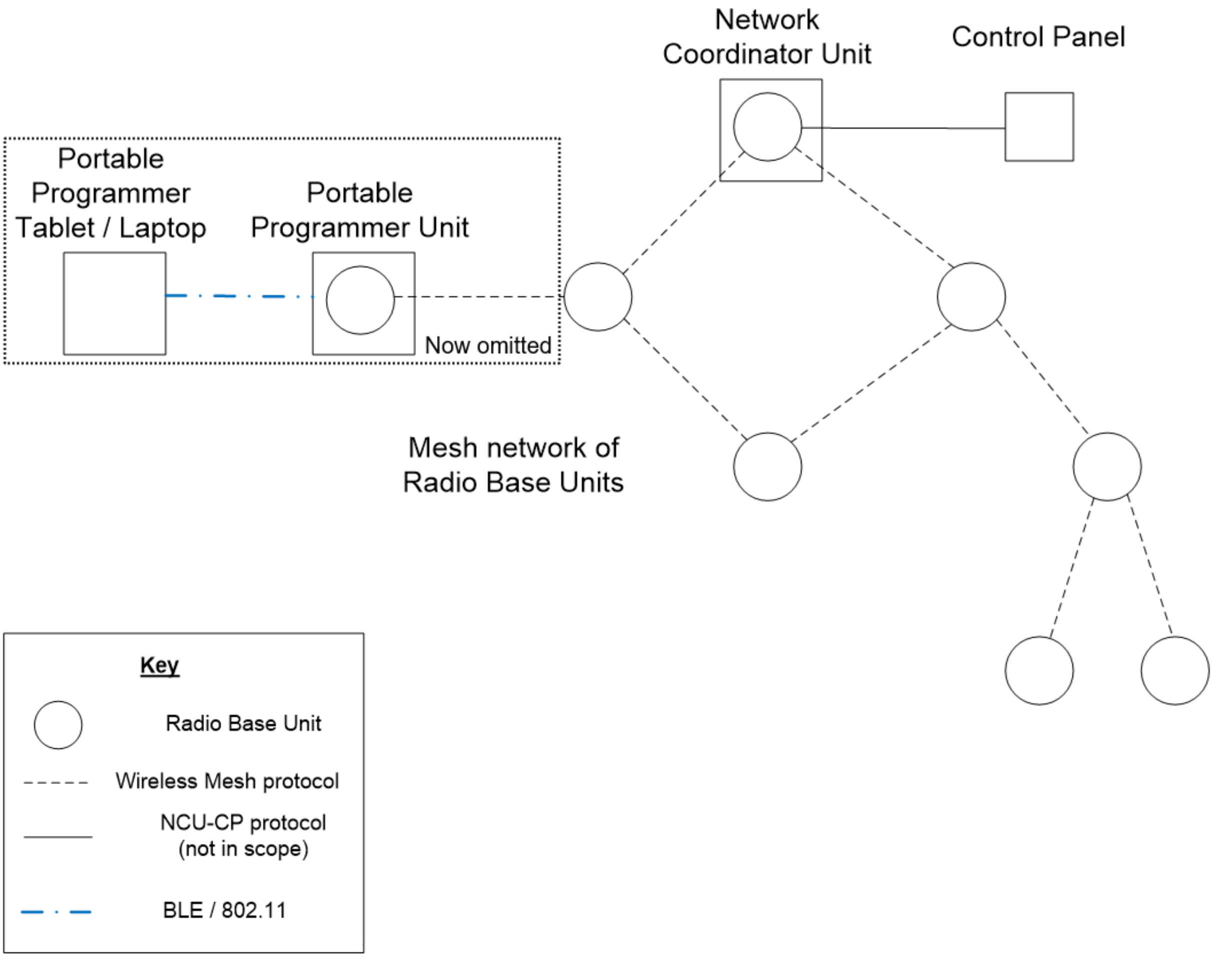


Figure 3: Wireless Mesh Network

1.7 Interfaces

Name	Description
Mesh radio interface	Internal interface between Radio Base Units. Communication uses the Wireless Mesh Protocol over a wireless link.
NCU-CP interface	External interface between Network Coordinator Unit and Control Panel. Communication uses the NCU-CP protocol (not in scope) over a wired connection.
PP-RU interface	Internal interface between Portable Programmer and Remote Unit. Communication uses the PP-RU protocol over a wired or wireless connection (See Section 9). Use now omitted.

Table 1: System Interfaces

2 SCOPE

This document describes the wireless mesh protocol and the Portable Programmer to RU protocol, latter now unused. This covers wireless communications between the following network elements:

- Network Coordinator Unit and Remote Unit
- Remote Unit and another Remote Unit
- Portable Programmer and Remote Unit

The document also covers the AT commands used in the wired communications between Portable Programmer and Remote Unit.

Communication between the Network Coordinator Unit and the Control Panel is outside the scope of this document.

3 SAFETY AND ASSURANCE

This section describes how safety and assurance have been considered in the design of the mesh protocol and how these will be handled in the implementation phase.

3.1 Safety

The Cygnus 2 system will be used to detect fires in operational scenarios. It is a design aim that the system performs the following actions reliably:

- Detects fires and reports this to the control panel
- Enables output devices (sounders and beacons) when instructed by the control panel

In addition to this, the system should have a low false alarm rate and must be able to reliably turn off output devices when instructed by the control panel. Failure to achieve these may reduce confidence in the system.

The following approach has been taken in the design of the mesh protocol to address these aims:

- The design has been kept as simple as possible
- The design has been based on existing wireless systems that have been in use for several years and have been proved operationally. This includes Wireless HART and IEEE Time Slotted Channel Hopping (TSCH).
- The potentially problematic areas of the design have been simulated to give confidence that they will meet the requirements

During the development we have used the following approaches to address these aims:

- Using a subset of the MISRA C rules in the implementation because this is an established way of reducing software bugs
- The software has been tested during initial development using a unit test framework
- Selected parts of the code have been subject to review

3.2 Reliability

The mesh protocol has been made as reliable as possible by:

- Adopting a simple design based on proven techniques (e.g. slotted ALOHA)
- Verifying the design through simulation

The system will be used in radio spectrum in the Industrial, Scientific and Medical (ISM) band that is shared with other users. Interference from other users of this spectrum will vary from installation to installation, and will probably vary with time for each installation. And so we have adopted a best endeavours approach to communications over the radio links. This is made as reliable as reasonably possible by:

- Employing path diversity through the mesh
- Acknowledging transfers in the uplink and retransmitting if messages are lost
- Retransmitting important messages on the downlink
- Using frequency hopping techniques

The software implementation has been made reliable by:

- Automated unit tests
- Peer review
- Use of a coding standard with MISRA C subset

A Failure Mode and Effects Analysis (FMEA) is planned for the mesh.

3.3 Maintainability

The protocol has been specified using standard protocol layers. This follows the approach taken in many other radio protocols. It also allows the protocol to be broken down into modules for implementation.

The software has been designed with a sensible modular structure that reduces coupling and increases cohesion.

The software will be implemented using a coding standard. This will make maintenance easier for engineers (assuming they are familiar with the standard).

An automated unit test framework was created and tests written for the framework. This had the advantage that existing functions could be checked whenever changes were made to the code base.

This document describes the mesh protocol document and the PP to RU protocol. It is intended to clearly describe the design of the protocol, and assist maintainers.

The design divides the transmitted protocol into logical channels, assigning several dedicated slots to each logical channel. The ratio of slots allocated to different logical channels may be adjusted if necessary, to balance the relative performance and latency in the uplink and downlink directions, based on the performance indicated by simulations.

3.4 Quality

The Jira tool has been used for managing tasks, issues and risks. A cloud-based project was set up in Jira that could be accessed by both the PA and Bull teams.

Progress was tracked using an MS project plan, and now a spreadsheet.

The project initially used the PA Quality Management Procedures, including:

- QP549 Change Requests
- QS505 C Coding Standard
- QP377 Software Code Review
- QP341 Software Release

The project transitioned to using the Bull Quality Management Procedures, including:

- 100-PRO-0001-04 Quality Management Document and Record Control Procedure
- 100-STD-0003-01 Software C Coding Standards
- 100-PRO-0005-01 Code Review Procedure
- Software Release procedure due to be created

4 PROTOCOL ARCHITECTURE

The mesh protocol architecture has a structure that is commonly used in wireless systems. It is divided into four layers, where each layer uses the services provided by the layer below. The layers are based on the ISO standard 7 layer model for protocols.

The architecture is shown in Figure 4.

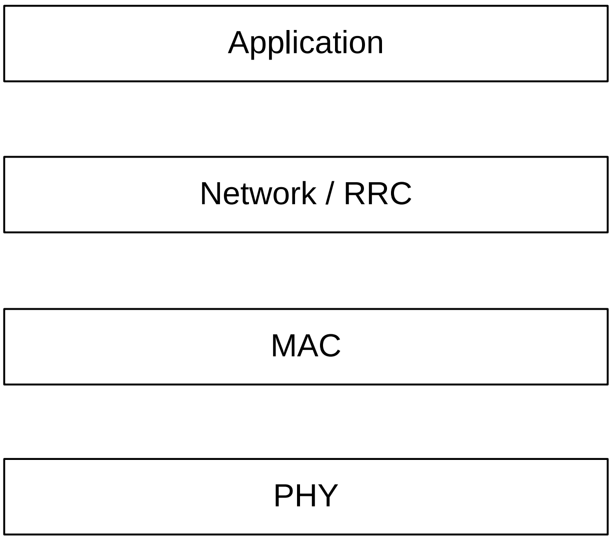


Figure 4: Protocol Architecture

The functions of each layer are described in the paragraphs below:

The **Application** layer provides the functions that are specific to this system. This includes the messages to report that a fire has been detected and to turn on the outputs. It also includes management and control functions to read parameters from remote units and write parameters back.

The **Network / RRC** layer has two roles:

a) The network layer is responsible for routing messages across the network. It handles uplinked messages (toward the NCU) and downlinked messages (from the NCU).
b) The Radio Resource Controller (RRC) is responsible for establishing the mesh during installation and then maintaining the mesh. This involves selecting which nodes to use when sending uplink messages to the NCU, which nodes to monitor to achieve and maintain system timing, and which nodes to monitor for the purpose of error detection and reporting.

The **MAC** (Medium Access Control) layer is responsible for coordinating access to the radio media. It supports the following channel types:

- Random Access Channel 1 (RACH1) - for fire detection traffic
- Random Access Channel 2 (RACH2) - for other uplink traffic

- Downlink Common Channel (DL-CCH) - for ad-hoc downlink traffic
- Dedicated Channel (DCH) - for scheduled 'heartbeat/sync' transmissions

The MAC uses a slotted Time Division Multiplexed (TDM) approach in which all the remote units are synchronised. The slots are permanently allocated to the above channels.

The **PHY** (physical) layer is responsible for transmitting and receiving frames of data. This uses LoRa which is a proprietary technique from Semtech. LoRa employs a spread spectrum approach that uses chirps to transfer data. The PHY is responsible for:

- Interfacing directly to the LoRa modem
- Transmitting and receiving packets of data
- Detecting the presence of ad-hoc packets on DL-CCH and RACH channels using the LoRa Channel Activity Detector (CAD)
- Transmit power control

This document is structured per the software architecture. Each layer in the protocol stack is described in a separate section of the document.

5 PHYSICAL LAYER

5.1 Summary of Key Design Decisions

The following design decisions have been made. The subsequent sub-sections describe also the alternatives, and provide key information that led to the decisions.

Parameter	Selection	Justification
Operating Frequency	Ten discrete channels in the band 865.0 to 868.0 MHz, with 300kHz channel separation.	See Section 5.2 for a detailed comparison of the considered alternatives.
LoRa Modulation Bandwidth	250kHz	The only viable options are 125kHz or 250kHz, being the only bandwidths permitted by OFCOM in the UK 865.0 to 868.0 MHz band that allow for sufficient channels. 125kHz would support 15 channels, and 250kHz would support 10 channels. 500kHz modulation bandwidth would support only 4 channels, which might prove restrictive for channel hopping. It was agreed in discussion between PA and Bull to use 250kHz, as bursts are approximately half the duration of 125kHz bursts, and thus system latency is halved.
Max Transmit Power (at output of LoRa modem)	10 dBm (on RFO pin)	The maximum power permitted by OFCOM in the 865.0 to 868.0 MHz band is 6.2dBm per 100kHz (equivalent to 10.2dBm per 250kHz).
Spreading Factor	7	The options for spreading factor are 6, 7, 8, 9, 10, 11 and 12. Each increment to the spreading factor approximately doubles packet duration. Compliance with the EN54 latency requirements across the mesh initially drove the decision to use the lowest spreading factor, 6, to deliver the shortest packet durations, thus minimising the latency. Reliablity issues encountered with spreading factor 6 caused a switch to 7.[1]

[1] The document has been updated to spreading factor 7 values. Though spreading factor 6 values are in some cases shown too. This for traceability to the previous document revision, and to document the effect of change.

Packet Payload Sizes	Fixed, per channel NCU • DCH 11 bytes • DL-CCH 22 bytes • RACH 22 bytes • RACH ACK 10 bytes Portable Programmer, Firmware Update • Downlink 255 bytes • Uplink 12 bytes	Spreading factor 6 as initially used supports only use of LoRa 'implicit header', and thus the receiver must know in advance the size of the packet it is receiving. The switch to spreading factor 7 allows instead use of LoRa 'explicit header'. However 'implicit header' use is retained to not alter design. Also to preserve the battery-life and reduced latency benefit of minimised 'on-air' time.
Channel Hopping	Supported. 10 channels per system.	BRE, Intertek and FireQuest have all stated their belief that the EN54-25 test for 'Compatibility with Other Band Users' would fail if a radio link is limited to a single channel

5.1.1 Configurable LoRa Modem Parameters

The configurable parameters of the LoRa PHY and the proposed values for Cygnus II are as follows:

Table 2: LoRa PHY Parameter Settings

Parameter	Parameter Range	Proposed Values
Packet Size	1 to 255 bytes	DCH 'Heartbeat' packets are 11 bytes DL-CCH and RACH packets are 22 bytes RACH ACK packets are 10 bytes Portable Programmer firmware update downlink 255 bytes Portable Programmer firmware update uplink 12 bytes
Spreading Factor	6 to 12	7 (formerly 6)
Bandwidth (kHz)	7.8, 10.4, 15.6, 20.8, 31.25, 41.7, 62.5, 125, 250 or 500 kHz	250kHz
Coding Rate	4/5, 4/6, 4/7 or 4/8	4/5 rate. This gives the shortest packets, and hence the longest battery life and the lowest latency. However, it does reduce the maximum range per hop, compared with other coding rates.

Transmit Power	20, 17, 13 or 7 dBm These are maximum values – can also be set to lower Tx powers.	7dBm or 13dBm (UK). In the latter case, transmit power would be reduced by 3dB using fixed power level implemented on the LoRa modem, in order to not exceed the 10.2dBm limit permitted by OFCOM in the 865.0 to 868.0 band. Other countries are TBD.
Frequency Hopping	LoRa supports frequency hopping within packets.	LoRa frequency hopping will not be used (UK). LoRa frequency hopping may be required for USA and other markets (TBD).
Radio Bands	Band 1 (868/915 MHz) Band 2 (433 MHz) Band 3 (169 MHz)	Channels will be programmed in the region 865.0 to 868.0 MHz (UK). Other countries are TBD. The LoRa modem will be re-programmed when necessary to use one from ten hopping channels at 300kHz intervals.

5.2 Radio Channel Allocations

The current version of Cygnus II will operate in the 865-868 MHz band (the protocol design will need to be updated for operation at 915 MHz). It uses a fixed modulation bandwidth of 250 kHz, and uses 10 channels with centre frequencies given by 865.20 MHz + N*300 kHz, where the channel number N takes the value 0 to 9. The key design decisions are summarised below.

- The packet durations associated with 125 kHz bandwidth would make it difficult to achieve the message latency requirements of EN54 for all but very shallow meshes. Using 250 kHz modulation bandwidth allows all packet durations to be halved compared to using 125 kHz.
- Operating in the 865-868 MHz band will support up to 10 different radio channels for BW=250 kHz with transmit power 6.2dBm per 100 kHz (equivalent to 10.2dBm per 250kHz) and duty cycle up to 1% (or unlimited duty cycle if 'polite access' is employed, i.e. Listen Before Talk (LBT) and Adaptive Frequency Agility (AFA) – see ETSI EN 300 220-1 V3.1.1 Section 5.21 [18]).
- Operating up to six 250 kHz channels in the 863 to 865 MHz band would present a duty cycle limit of 0.1% (unlimited duty cycle if 'polite access' is employed), but significantly would be limited to a transmit power of -0.5dBm in a 250 kHz bandwidth. N.B. the Semtech Application Note 'ETSI Compliance of the SX1272/3 LoRa Modem' [15] does not list any compliant channels in the 863 to 865 MHz band.

- Operating up to five[2] 250 kHz channels in the 868 to 870 MHz band would allow a variety of different duty cycle limits of 0.1%, 1.0% and 10% in different channels (unlimited duty cycle if 'polite access' is employed), but with no restrictive limits on transmit power. However, legislatively speaking, this is a complicated portion of the band. EN 300 220-1 V2.4.1 (2012-01) [19] Table 5 defines nine sub-bands in this frequency range, each with different regulations, and is further covered by two overlapping descriptions as per the sub-bullets below. It is not clear to us how the overlapping regulations should be applied. N.B. the Semtech Application Note 'ETSI Compliance of the SX1272/3 LoRa Modem' [15] lists only two compliant 250kHz channels in the 868 to 870 MHz band.
  - 865.0 to 870.0 MHz, -4.5dBm per 100kHz (3.2dBm in 250kHz)
  - 863.0 to 870.0 MHz, -0.8dBm per 100kHz (-0.5dBm in 250kHz)

OFCOM regulations for the UK deployment in the 865-868 MHz band limit the duty cycle for any one device to 1%, and the transmit power to 6.2dBm per 100 kHz (equivalent to 10.2dBm per 250kHz). We operate the LoRa module with maximum transmit power of 7 or 10 dBm which prioritises battery life above hop distance.

5.2.1 UK Regulation of 868MHz Band

OFCOM regulates the use of the 868MHz band as shown in Table 3 below.

Table 3: UK Regulation of 868MHz Band

Band (MHz)	Bandwidth (MHz)	Applications	Power (mWatts, unless specified otherwise)	Max Chan Spacing	Duty Cycle (%)
863.0-870.0	7.0	Non-specific, Narrow/Wideband modulation	25	100 kHz	0.1, or LBT + AFA
863.0-870.0	7.0	Non-specific, DSSS or wideband, not FHSS	-4.5dBm/100kHz	N/A	0.1, or LBT + AFA
865.0-870.0	5.0	Non-specific, DSSS or wideband, not FHSS	-0.8dBm/100kHz	N/A	0.1, or LBT + AFA
865.0-868.0	3.0	Non-specific, DSSS or wideband, not FHSS	6.2dBm/100kHz	N/A	1.0, or LBT + AFA
863.0-870.0	7.0	Non-specific, FHSS	25	100 kHz	0.1%, or LBT

[2] EN 300 220-2 V3.2.1 (2018-06), [20] Table C.1 'National radio interfaces not EU wide harmonised', states that the 863.0 to 870.0 band excludes the alarm bands, but not social alarms, which is why we have claimed that only five channels could be operated in this 2.0 MHz sub-band instead of six.

868.0-868.6 868.7-869.2 869.4-869.65 869.7-870.0 869.7-870.0	0.6 0.5 0.25 0.3 0.3	Non-specific use	25 25 500 25 5	N/A N/A 25 kHz N/A N/A	1.0, or LBT + AFA 0.1, or LBT + AFA 10.0, or LBT + AFA 1.0, or LBT + AFA No restriction
864.8-865	0.2	Wireless Audio	10	50 kHz	No restriction
868.6-868.7 869.25-869.3 869.3-869.4 869.65-869.7	0.1 0.05 0.1 0.05	Alarms (Cygnus I)	10 10 10 25	25 kHz 25 kHz 25 kHz 25 kHz	1.0 0.1 1.0 10
869.2-869.25	0.05	Social Alarms	10	25 kHz	0.1

5.2.2 ETSI Compliance of SX1272/73 LoRa Modem

Based on the Semtech Application Note 'ETSI Compliance of SX1272/73 LoRa Modem' [15], the radio configurations shown in Table 4 have been declared as ETSI compliant.

Table 4: ETSI Compliance of SX1272/73 LoRa Modem

Band (MHz)	ETSI Power Limit (dBm)	LoRa Modulation BW (kHz)	SX1272 Tx Power (dBm)	Max No. Of Channels	Max Duty Cycle (%)
865.0-868.0	6.2 per 100 kHz	500 250 125	6 6 6	4 10 15	1.0 1.0 1.0
868.0-868.6	14	250 125	13 13	1 3	1.0 1.0
868.7-869.2	14	250 125	13 13	1 2	0.1 0.1

869.4-869.65	20	125	20	1	10.0
869.7-870	7 14	125 125	6 13	1 1	100 1.0

5.3 Packet and Preamble Durations

The packet and preamble durations for each of the channel types are shown in Table 5. Parameters common to all packet types are listed in the bullets. The time-on-air values have been calculated using the LoRa Calculator tool, downloaded from the Semtech website.

- Bandwidth is 250kHz
- Spreading Factor is 7 (formerly 6)
- Explicit header mode is disabled (mandatory for SF6)
- CRC is disabled (Cygnus II CRC is handled within the payload, and does not use the LoRa CRC)
- Coding rate is 4/5

Table 5: Packet Sizes Selected for Cygnus II

Channel	Programmed Preamble (Symbols)	Preamble Duration (ms)	Payload Size (Bytes)	Time on Air (ms)	Max Payload Size (Bytes) for given Time on Air
DCH	16	10.37	11	22.14	14
DL-CCH	20	12.42	22	30.78	23
RACH	16	10.37	22	28.73	23
RACH ACK	16	10.37	10	19.948	13
PP F/W Update (Downlink)	20	12.42	255	203.39	255
PP F/W Update (Uplink)	20	12.42	12	24.19	13

The final column, “Max Payload Size (Bytes)”, refers to the maximum number of bytes that the packet can hold for the given Time on Air value. (The Time on Air increases in increments of 5 symbols each time the payload is increased by 3 bytes.) Larger payloads could be transported provided that the increase in Time on Air is acceptable to the slot structure.

Two preamble sizes are supported:

- The long preamble (12.42ms) is used for the DL-CCH channel. The receiver does not explicitly know when these packets will be sent, and so uses a single Channel Activity Detector (CAD) as the means of detecting the presence or absence of the packet.
- The short preamble (10.37ms) is used for the DCH (timing synchronisation message), RACH and RACH acknowledgements. In the case of DCH and ACK messages the receiver can predict that a message

should be arriving, and simply opens a receive window without first using the CAD. The arrival of a RACH message is unpredictable and is detected using the CAD before enabling the receiver.

Figure 5 depicts the earliest and latest arrivals of the long preamble, arriving from two parents having routes to the NCU with the most extreme of timing errors that span the entire 4.0ms available guard space. In order for a single CAD event to detect both preambles the duration of the preamble must therefore be at least 0.980ms (CAD duration) + 5.760ms (7 symbol preamble being minimum found reliable) + 4.0ms (max mesh-path timing spread) = 10.740ms. Since the preamble length options are granular, the actual minimum is 10.880ms.

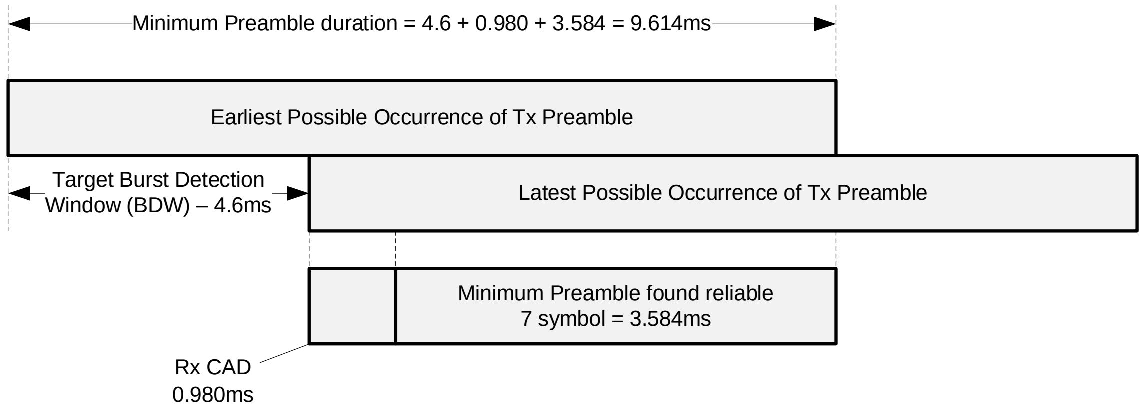


Figure 5: Preamble Duration, Burst Detection Window (BDW) and CAD Duration (Not to Scale)

5.4 Portable Programmer - Firmware Update

To perform the firmware update, the NCU must first broadcast a message on the DL-CCH that notifies all devices to switch to firmware update mode at the end of the current long frame. The firmware update process then commences at the end of the current long frame. At the end of the firmware update process the PP instructs the node to re-join the mesh by following the Resynchronisation procedure defined in Section 6.4.2. Whilst in firmware update mode:

- The node operates in Rx Continuous mode, as defined in Semtech SX1272/73 datasheet (Rev . 4 - January 2019) [16] Figure 11 and the Rx Continuous use case described on page 38.
- Downlink packets may be sent ad-hoc, i.e. not adhering to any slot structure. Uplink messages may be sent in response, also not adhering to any slot structure.

Note that duty cycle limits do not apply during installation, commissioning or maintenance[3], and so the portable programmer may operate without a duty cycle limit.

If the portable programmer is operated whilst the rest of the mesh is in operation, it may be preferable to switch to a different RF channel to those used by the mesh. Refer to Table 4 for possible options.

[3] "Procedures such as setup, commissioning and maintenance are not considered part of normal operation", ETSI EN 300 220-1 V3.1.1 (2017-02), Section 5.4.2.

5.5 Polite Spectrum Access

In order to go beyond the duty cycle limits imposed on each sub-band (typically 1% in the sub-bands we are targeting), a scheme now referred to as Polite Spectrum Access (PSA) can be employed, and in which case all duty cycle limits are removed. PSA is defined in EN 300 220-1 V3.1.1 and is effectively the combination of Listen Before Talk (LBT) and Adaptive Frequency Agility (AFA). In summary, before transmitting on a given channel, the transmitter agrees to measure the RSSI on that channel, and if it is below a specified threshold then the channel is deemed to be available and the unit is permitted to transmit. If the channel is not available, then the unit can either a) defer transmission on that channel by a random multiple of a minimum deferral period, or else it can repeat the LBT.

PA recommended against implementing this feature. A reason for which being that in the case of the sync messages, excessive drift may occur in a dependent node if a succession of sync messages cannot be transmitted; note that just because the LBT detects a signal does not mean that its own transmission might not still be detected by dependent child and parent nodes. Another implication is that if a succession of sync messages cannot be transmitted by a node, its parent nodes may conclude that the node is not working, and may report it as a fault to the NCU.

For these reasons, PA recommended not implementing PSA unless simulation results indicate that the duty cycle in normal operation might exceed 1%. See Section 5.10.2 for duty cycle estimates.

5.6 RTC Interrupts and Fractional-N Division

Frequency synchronisation will be achieved by fractional-N division of the MCU LPTIM timer in order to generate interrupts at the start of all appropriate slots (it can skip unwanted slots to save power). The fractional-N division is implemented in software, and the hardware interval timer is reprogrammed with each successive wake-up of the MCU.

The timing in a receiving node will slowly drift relative to other nodes until it is corrected by programming the divider with a different interrupt interval, at which point a slight jump in timing will occur: the interrupts are thus generated with a small amount of timing jitter. It should be noted that the incoming packet will also be subject to some jitter of its own, introduced by the fractional-N timing of the transmitting device, which will not be correlated with the fractional-N jitter of the receiving device. The jitter in the transmitter and the jitter in the receiver will both be +/-0.5 LPTIM clock periods (relative to a local mean value), so the total relative jitter should not exceed +/-1 LPTIM clock periods. This is not expected to cause a problem.

(Note also that timing jitter will propagate outwards through the mesh, away from the NCU, since the jitter will be detected and to some extent replicated by each dependent node. We thus expect more jitter to be exhibited at the extremes of the mesh than near its centre. We might assume potentially an additional +/-0.5 clock cycles of jitter to be introduced per hop. At five hop depth, this would be +/- 0.075ms.)

Figure 6 shows to rough scale the relative durations of the CAD window and the LPTIM clock intervals.

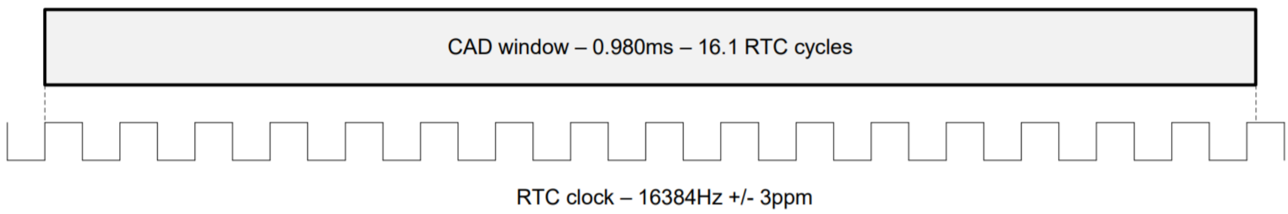


Figure 6: Comparison of CAD Duration and MCU LPTIM

5.7 Frequency Stability Assessment for Radio Crystal

The Semtech LoRa FAQ document states that the LoRa receiver is capable of operating using a +/- 10ppm crystal for bandwidths of 62.5kHz or higher. Infact a +/- 3ppm Temperature Compensated Crystal Oscillator (TCXO) is used.

5.8 Channel Activity Detector

The Channel Activity Detector (CAD) is a means of detecting the presence of a LoRa modulated preamble. It is able to detect a preamble that has lower power density than the channel noise, and is thus more effective than using an RSSI measurement that would be limited by the contribution of the noise to the power measurement. Note that the detection sensitivity of the CAD is approximately 3dB worse than the detection sensitivity for the packet receiver, which means that packets with weaker signal strengths will not be detected, even though they could in theory be decoded.

The CAD will be used to detect the presence of any packet on the RACH1, RACH2 or DL-CCH channels. The packets on all these channels are sent on demand, and hence for power-efficiency the receiver must use the CAD to check for the presence of any packet before opening the full receiver.

The CAD will not be used on the DCH or on RACH Acknowledgments, since in both cases those transmissions are scheduled and the receiving node will simply open a receive window.

Parametric Overview of Channel Activity Detector

Symbol Duration (in seconds) = (2^SF) / BW (BW in Hz, SF is Spreading Factor)

Typical CAD Duration (in seconds) = Above x CAD duration (in Symbols from datasheet Figure 13)

Of this period the radio is in receiver mode for (2^SF + 32) / BW seconds. For the remainder of the CAD cycle the radio is in a reduced consumption state.

Table 6: CAD Duration for Various Configurations

SF	CAD Duration (Symbols)	Typical CAD Duration (ms) Bandwidth = 125 kHz	Typical CAD Duration (ms) Bandwidth = 250 kHz	Typical CAD Duration (ms) Bandwidth = 500 kHz
6	2.25	1.152	0.576	0.288
7	1.915	1.961	0.980	0.490
SF	CAD Duration (Symbols)	CAD initially in Rx Mode (ms) Bandwidth = 125 kHz	CAD initially in Rx Mode (ms) Bandwidth = 250 kHz	CAD initially in Rx Mode (ms) Bandwidth = 500 kHz
6	2.25	0.768	0.384	0.192
7	1.915	0.128	0.064	0.032

Table 7: CAD Current Consumption for Various Configurations

SF	Bandwidth (kHz)	Full Rx, IDDR_L (mA)	Processing, IDDC_L (mA)	Average CAD Current (mA) Based on durations of IDDR_L and IDDC_L
6	125	10.8	5.6	9.1mA Based on IDDR_L (66.7%) + IDDC_L (33.3%)
6	250	11.6	6.5	9.9mA Based on IDDR_L (66.7%) + IDDC_L (33.3%)
6	500	13	8	11.3mA Based on IDDR_L (66.7%) + IDDC_L (33.3%)
7	125	10.8	5.6	9.0mA Based on IDDR_L (65.3%) + IDDC_L (34.7%)
7	250	11.6	6.5	9.8mA Based on IDDR_L (65.3%) + IDDC_L (34.7%)
7	500	13	8	11.3mA Based on IDDR_L (65.3%) + IDDC_L (34.7%)

5.9 LoRa Receiver

The LoRa receive mode is enabled whenever a packet is known to be available, either because it is scheduled on the DCH, is a RACH ACK, or because a preamble has been detected by the CAD.

This is highly efficient for the scheduled packets, as the receive window need only be opened when a message for the receiving RU is expected.

However, there is an inefficiency when used with un-scheduled packets, since all packets within detection range of the receiver must be decoded in order to decide whether the packet is intended for the receiving RU. This effect is exacerbated by two separate issues, summarised below:

- Since EN54-25 mandates a minimum attenuation reserve of not less than 10dB in the link budget, the detection radius must necessarily exceed the maximum hop radius, and assuming an inverse-square power law for radiated power, this corresponds to a ratio of SQRT(10) = 3.16.
- Since the traffic handled by an RU of rank 1 (one hop from the NCU) includes all the traffic of its descendent nodes, there is a rapid growth in traffic density as we approach the NCU. In a mesh with uniform distribution of devices, the total mesh traffic is approximately four times the number of source packets (i.e. those that are not mesh repeats).

Combining these two effects over the entire traffic in the mesh, a very significant number of packets might be decoded unnecessarily.

Note however that this analysis assumes an inverse square law, whereas in practice the signal level is likely to fall off far more quickly: an Ofcom report suggested that an inverse fourth power is more realistic in a multi-dwelling building, and attenuations of 20dB are typical for a signal passing through the outer wall of a building.

One approach to reducing the number of unnecessary decodes would be to distribute the traffic across multiple channels, in a similar way to that described for DL-CCH in Section 6.2.2, though such a technique is not currently described in this document.

Table 8: Receiver Current

LNA Boost	Current (mA)	Notes
Off	9.7 to 12 9.7 @ BW = 125 kHz 10.5 @ BW = 250 kHz 12 @ BW = 500 kHz	Varies with bandwidth (125 to 500 kHz)
On	10.8 to 13 10.8 @ BW = 125 kHz 11.6 @ BW = 250 kHz 13 @ BW = 500 kHz	Varies with bandwidth (125 to 500 kHz)

5.10 LoRa Transmitter

5.10.1 Transmit Power and Power Control

The Semtech LoRa modem has the following three RF power amplifier blocks. PA0 is the block used.

- PA0 A high efficiency amplifier capable of yielding RF power programmable in 1 dB steps from -1 dBm to +14 dBm directly into a 50 ohm load with low current consumption. PA0 is connected to pin RFO (pin 24).
- PA1 & PA2 These are both connected to pin PA_BOOST (pin 27). There are two potential

  configurations of these power amplifiers, fixed or programmable. In the fixed configuration they can deliver up to +20 dBm. In programmable configuration they can provide from +17 dBm to +2 dBm in 1 dB programmable steps. Naturally, low impedance matching and harmonic filtering is required to ensure RF power delivery and regulatory compliance

The amplifiers are controlled using the 4-bit register OutputPower to set the transmit power in the range -1 to +14 dBm for PA0. Or for PA1 & PA2, +2 to +17 dBm, or +5 to +20 dBm with high output power +20 dBm settings using register RegPaDac.

Cygnus II will be limited by ETSI regulations to a maximum 6.2dBm per 100kHz (equivalent to 10.2dBm per 250kHz), when operating in the 865-868 MHz band, as described in Table 4. Hence we operate the PA0 amplifier with OutputPower set to 10, giving 9 dBm, termed maximum power.

However, the transmit power can usefully be reduced in operation, subject to maintaining the EN54-25 specified minimum attenuation reserve. Such reduction in power would save battery power and minimise the number of other RUs that will be able to detect and therefore need to decode the transmitted packets.Two power levels are used by the radio devices. High power is applied for fire signals and low power is used for routine traffic. The power levels are programmable and are set on installation (probably based on a site survey).

A dynamic algorithm is utilised by the NCU. It remains dormant until the control panel power supply fails and the panel switches to battery operation. The power level is then set as low as possible for the weakest connected device to remain in contact. This is based on open-loop measurements, and assumes reciprocity in the path attenuations: i.e. a unit can infer the power at which it needs to transmit based on the received power in the reverse direction.

Some example current draws for the LoRa module in transmit mode are listed in Table 9.

Table 9: Current Draw of LoRa Modem for the Four Basic Transmit Power Options

Tx Power (dBm)	Current (mA)	Notes
20	125mA	RFOP = +20dBm. on PA_BOOST
17	90mA	RFOP = +17dBm. on PA_BOOST
13	28mA	RFOP = +13dBm. on RFO pin
7	18mA	RFOP = +7dBm. on RFO pin

The alternative dynamic power control algorithm will operate as follows:

- The NCU keeps a record of all connected devices, string the relevant attributes for each device.On switching to battery power, the NCU examines the records for the weakest received signal, based on RSSI. The Tx power is determined by applying the signal strength to a linear scale of power settings.
  - The NCU revises its power setting every long frame.

5.10.2 Duty Cycle Estimates

The average duty cycle over a 24 hour period has been calculated using spreadsheet *HKD-17-0047-D Power Calculation Spreadsheet.xlsx [22]*. Please refer to the spreadsheet for all assumptions.

Table 10: Duty Cycle Estimates for an RU (24-hour Period)

Bandwidth (kHz)	Spreading Factor	Estimated Duty Cycle for an RU
125	6	0.043%
250	6	0.027%

250	7	0.045%

The duty cycle limit of 1%, beyond which polite spectrum access would be required (PSA, see Section 5.5), is measured within a 1 hour period. The duty cycle in a 1-hour period for various events are described below: these assume the LoRa parameter settings described in Sections 5.1, 5.2 and 5.3.

These values are very significantly below 1%: there would have to be a very large number fire signals in a 1 hour period to breach the 1% duty cycle limit.

Table 11: Duty Cycle Estimates for an RU (Event-Based within 1 hour period)

Event Description	Duty Cycle per hour
One heartbeat per 193.64 sec	22.14ms DCH / 193640ms Long Frame = 0.0107% duty cycle
One fire signal per hour	(31.87ms RACH + 22.14ms ACK) / 3,600,000ms = 0.0015% duty cycle
One output signal per hour (with implicit 3 retransmissions)	(3 x 31.87ms DL-CCH) / 3,600,000ms = 0.0027% duty cycle
Mesh Forming and Healing Events	2 x (31.87ms RACH + 22.14ms ACK) / 193,750ms = 0.12% duty cycle (Minimum interval 193.75s: see 2000-SPC-0007 Mesh Forming and Healing [28])

The duty cycle of the NCU is expected to be generally lower for the above events, since no RACH transmissions are required (fire signals are received but not sent). Maintenance operations are excluded from the channel occupancy criterion.

6 MAC LAYER

The MAC layer uses a slotted TDM approach to multiplex a number of channels onto the PHY layer. This approach is based on the Time Slotted Channel Hopping (TSCH) approach used in IEEE Std 802.15.4.2015 [2]. This is a similar structure to WirelessHART [1].

6.1 TDM Structure

The TDM structure is depicted in Figure 7.

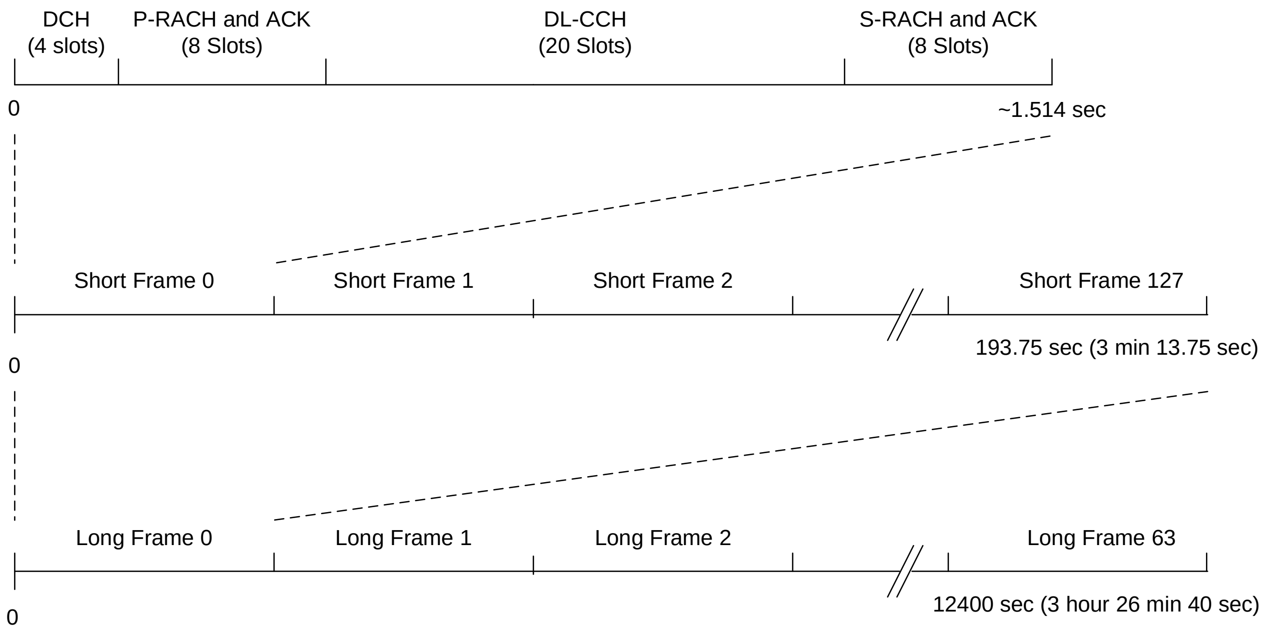


Figure 7: TDM Structure of Physical Layer

The TDM structure comprises slots of fixed duration of ~37.84ms, allocated as shown in Table 12.

Table 12: Frame and Slot Durations

Frame	Comprising	Duration
Slot	DCH, RACH, DL-CCH or ACK	~37.84 ms
Short Frame	40 slots (4 * DCH, 8 * RACH, 8 * ACK, 20 * DL-CCH)	~1.514 seconds
Long Frame	128 short frames	193.75 seconds
Super Frame	64 long frames	12,400 seconds

The choices of the values are explained below.

- The slot length has been selected as ~37.84ms (620 ticks * ($2*32768^{-1}$)) long. This suffices to accommodate the longest message, DLCCH, while leaving ~3.7ms trailing guard time, satisfying the 2ms minimum.
- Short frame duration is equal to the sum of its 40 component slots.
- A long frame is defined as a period equal to 128 short frames. This means that there are sufficient DCH slots to support 512 radio devices per NCU, including the NCU itself. Changing the number of short frames per long frame affects the channel hopping pattern sequence lengths described in HKD-17-0057-D Channel Hopping Algorithm [24].
- A super frame is defined as being 64 long frames in duration, however the repeat period of the RF channel hopping pattern on the DCH channel is just 16 long frames, and hence it repeats four times per super frame. This implies that typically the DCH hopping pattern will use six channels twice each, and four channels once each.

A breakdown of the active period within each slot is shown in Table 13. All durations are approximate except Guard Space. Minimum Slot Length gives Time On Air plus 4ms guard time, which would be the shortest that a slot could be reduced to for that particular channel type. The active periods and guard times for each channel type are described in more detail in Sections 6.2 and 6.3.

Table 13: Slot Durations and Minimum Slot Durations

Channel	Time on Air (ms)	Guard Space (ms)	Minimum Slot Length (ms)	Actual Slot Length (ms)
DCH	20.68	4	24.68	37.84
DL-CCH	30.78	4	34.78	37.84
RACH	28.73	4	32.73	37.84
ACK	19.95	4	23.95	37.84

There are a number of means available to modify the throughput of each logical channel, or to change the durations of the short, long and super frames.

- Table 13 Minimum Slot Length shows the minimum that could be used for each channel type, allowing a 2ms guard space at either end of the transmissions. These shorter slots could be used if necessary to increase the throughput of the channels, but at the expense of the extra complexity of managing the timing for mixed-size slots.
- RACH re-transmissions are based on an exponential back-off approach that is widely used in Slotted Aloha systems, such as Cygnus II. One possible modification would be to use variable offsets within a slot, plus Listen Before Talk (LBT) to help avoid collisions. This method, described in *HKD-17-0053-OP Compendium of Advanced Mesh Techniques* [23], would increase the RACH slot length, but has the benefit of compacting the timing spread of exponential back-off re-transmissions from an integer number of slots to a fixed fraction of that number. This will reduce the latency for collision resolution by one mesh node, at the expense of increasing the latency for propagating single messages across multiple nodes. The EN54 test-house BRE have advised that the former is often the reason for conformance test failures, and hence the method is of potential interest.
- Each node in the network is assigned a different DCH slot to send its heartbeat message. The slot is derived from the address of the node. The transmit cycle repeats every long frame. If the address of the node is A then the slot allocated for this node is as follows:

- Short frame index = A divided by 4
- DCH slot index = A modulo 4

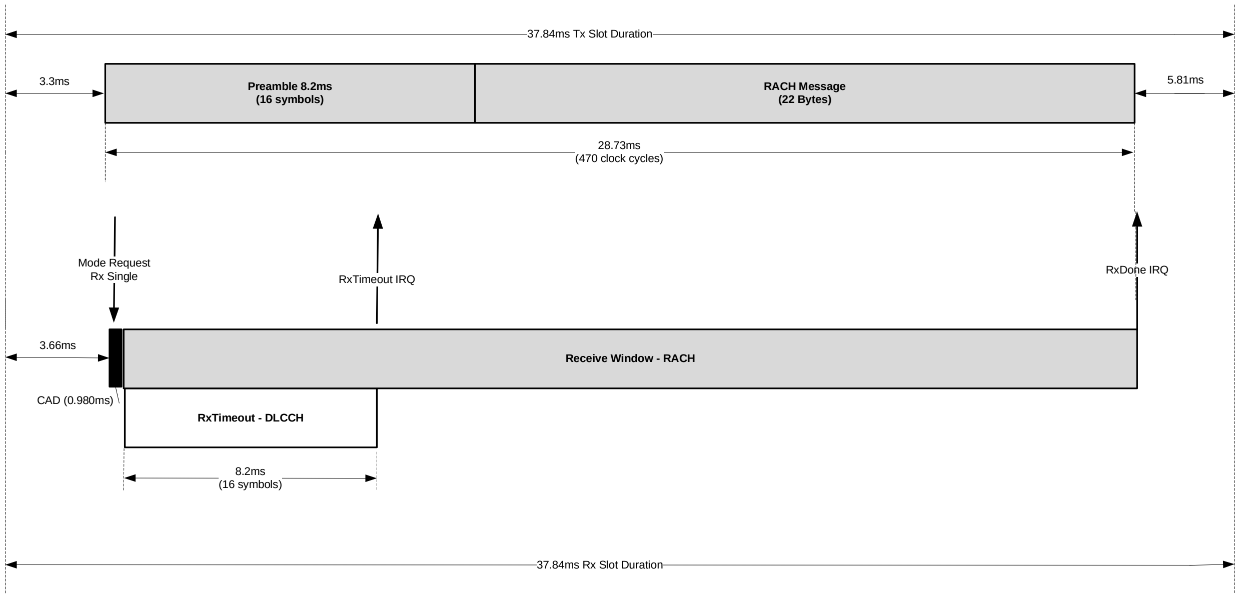
6.2 Slot Structure (DL-CCH)

The DL-CCH packet has the longest time on air of all CygnusII messages. The structure of a slot used for DL-CCH packets is depicted in Figure 8. A 2ms leading guard period is satisfied by the 3.3ms offset of transmission start from the beginning of the slot period. This accommodates any negative drift in the relative timing of the transmitting and receiving nodes. Inevitably drift will occur in both the transmitting and the receiving nodes, and the drift in each may combine in an additive or subtractive fashion. Note that drift must be accommodated not just between two adjoining radio nodes, but across entire paths across the mesh (the aggregated errors across two different mesh routes must be accommodated).

The guard periods are designed to be at least 2ms at each end of the slot. If slots are lengthened, the requirements on timing accuracy are loosened. But loosening means preamble duration must be extended, thus increasing the energy required to transmit and receive packets. The preamble is detected by a single instance of the Channel Activity Detector (CAD), with duration 0.980ms for 250kHz modulation bandwidth.

6.2.1 RACH Transmission

The (uplink) RACH can be transmitted in any slot allocated to a RACH channel. This maintained independently for Fire signals on the Primary (P-RACH) channel, and non-fire signals on the Secondary (S-RACH) channel. All nodes monitor all RACH slots using the CAD. Detection occurs on the RF hopping channel that is applicable to the entire mesh.



6.2.2 DL-CCH Transmission

Transmission on the (downlink) DL-CCH is an unacknowledged broadcast system in which each node repeats the message that it receives to propagate it down the ranks. This introduces the risk that nodes may broadcast at the same time. When nodes transmit in the same slot, and a receiving node sees them at a similar signal strength, the receiving node is unable to decode the message.

To address the risk of collisions we attempt to time-separate the transmission of the nodes in such a way that we minimise the opportunities for collisions to occur. Even with twenty DL-CCH slots available per short frame, collisions are inevitable in heavily populated networks.

Reliability is increased by transmitting each message three times (configurable) over three successive short frames. Each node changes the slot number and frequency channel on which it transmits for each short frame.

The slot number is calculated using the short frame index and the node ID. The frequency channel is selected from the downlink channel hopping sequence, offset by the node ID.

This enables the receiving node to calculate in advance the slot that its primary parent will broadcast in, allowing it to sleep through the other slots.

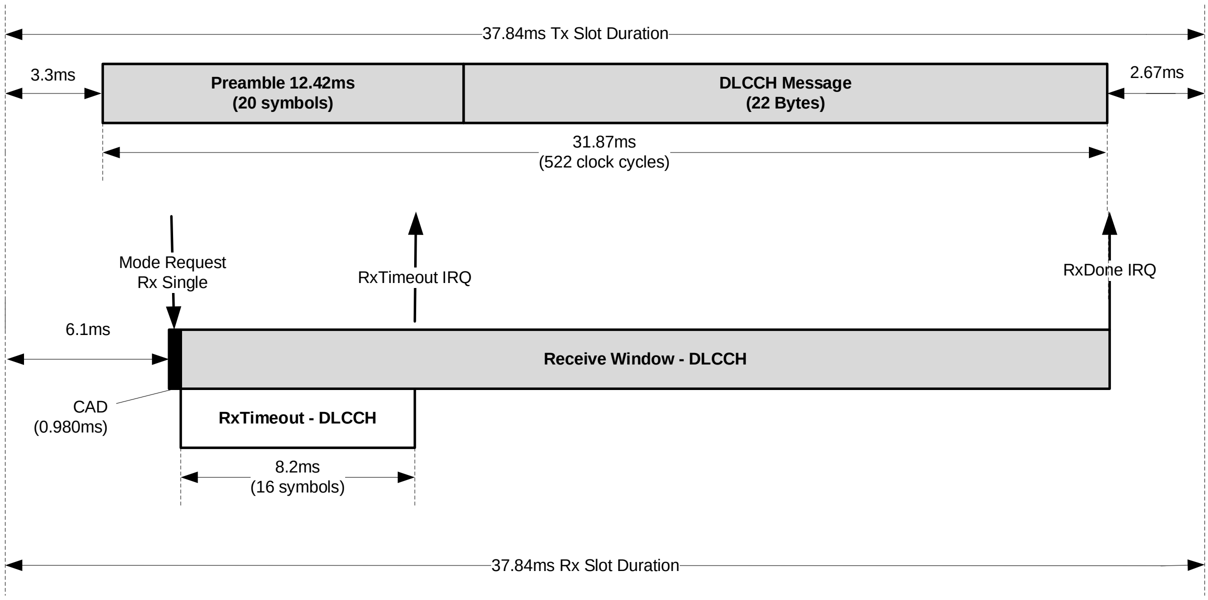


Figure 8: DL-CCH Slot Timing

6.3 Slot Structure (ACK)

The structure of a slot used for the ACK is shown in **Error! Reference source not found.**.

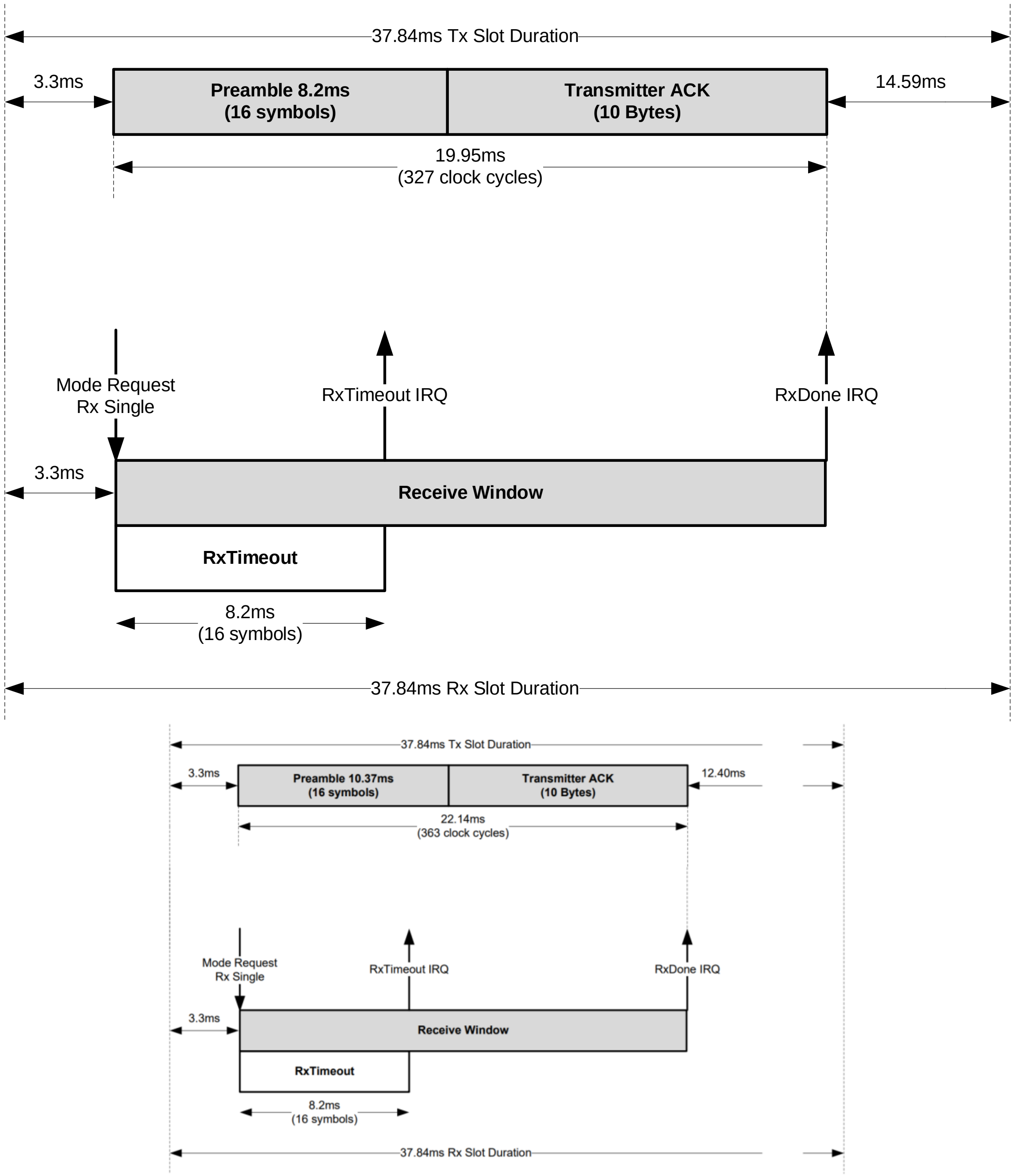


Figure 9: ACK Slot Timing and Burst Detection Window

6.4 Slot Structure (DCH) and Synchronisation Procedure

The structure of a slot used for the DCH is shown in Figure 10. The figure also shows the Burst Detection Window both for the Synchronisation Acquisition Phase and for the Synchronisation Tracking Phase.

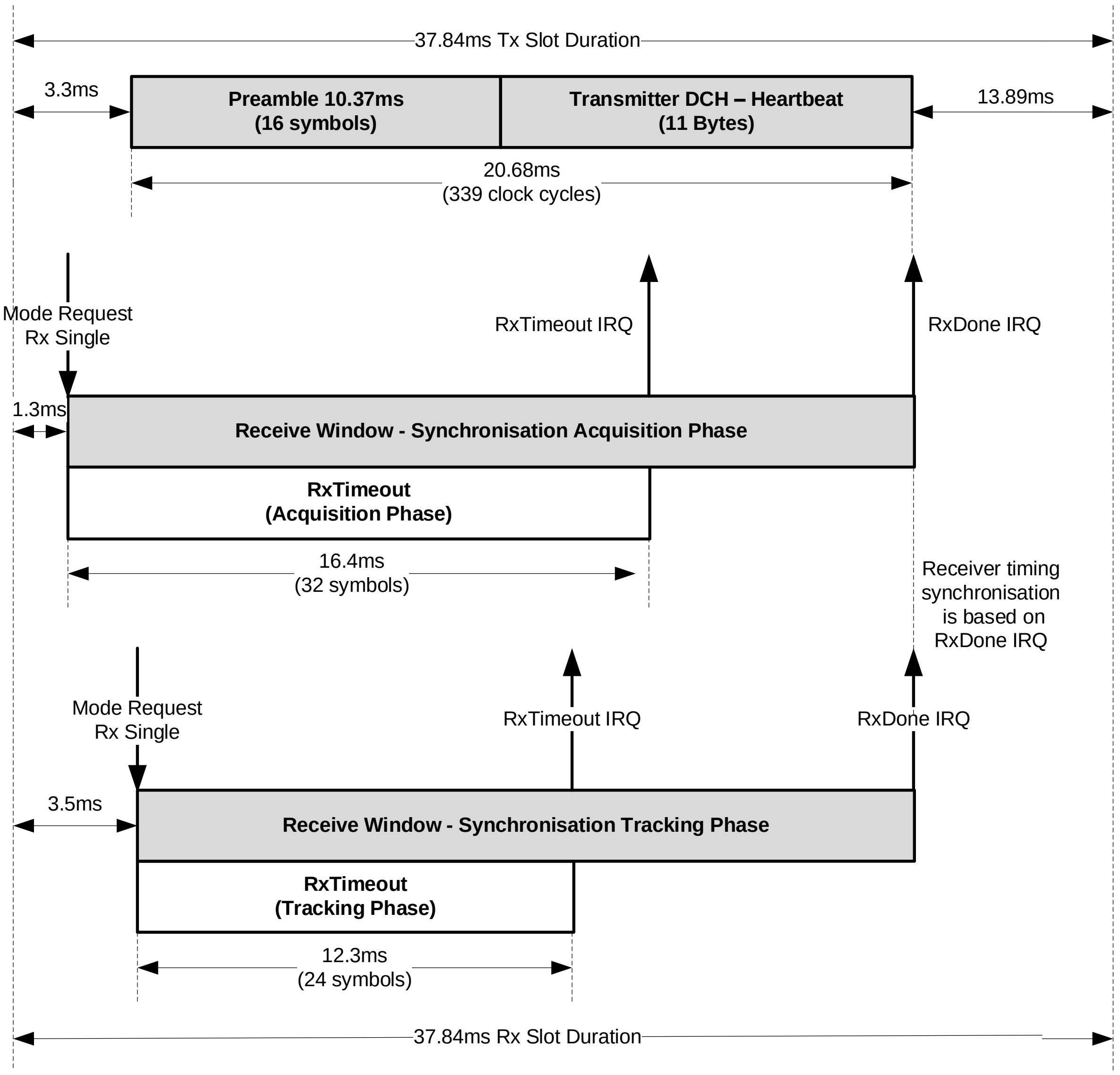


Figure 10: DCH Slot Timing and Burst Detection Window

6.4.1 Synchronisation

Synchronisation occurs during the installation phase, and is the process by which the entire mesh achieves timing and frequency synchronisation.

The purpose of synchronisation is to ensure that all transmitted bursts fall within the valid receive window of all viable receivers, and to align the channel hopping sequences. Note that the CAD is not used to detect the synchronisation message: The DCH is always detected by activating the LoRa receiver at the expected arrival time of the packet. Synchronisation will occur during the installation phase, allowing the mesh to form prior to the commissioning phase.

The synchronisation process occurs in two phases: an initial Synchronisation Acquisition Phase, and a subsequent Synchronisation Tracking Phase. Note that Channel hopping is disabled for synchronisation so that nodes can acquire system timing on a single frequency: This avoids attempts at receiving on the wrong RF channel, thus speeding up the process.

Synchronisation Acquisition Phase

- To find a first timing synchronisation message, the receive window is left open continuously until a packet is detected. Once a packet is found, it is decoded and tested to ensure it is a timing synchronisation message. If it is not, the process is repeated.
- Once a first synchronisation message has been found, system timing is then known, and the interval to subsequent sync messages can be estimated. This estimate will be based on the assumption that the MCU clocks in both the transmitting node and the receiving node are both 16,384Hz, (32,768Hz pre-scaled division by 2) and that the interval between DCH synchronisation messages is one long frame, as defined in Table 12.
- To find the subsequent sync message the receiver opens a 16.4ms burst detection window 2ms before the expected arrival of the sync message, to accommodate up +6.6ms and -10.7ms of drift per long-frame.
  - This will allow up 34ppm frequency error before fractional-N frequency correction between the receiver and the transmitter: e.g17ppm in the transmitter, and a further 17ppm of the opposite polarity in the receiver.
  - No other preamble should occur within the 16.4ms burst detection window, otherwise this might be detected instead of the desired heartbeat. Each transmitting node has a dedicated time slot to send its sync message and they is a minimum separation of one slot length(37.84ms), so the preambles of any other transmission should not fall within this window.

Synchronisation Tracking Phase

- After the slot interrupts from the RTC have had frequency correction applied (based on measuring the drift across a long frame), the receiver switches to using a 12.3ms burst detection window. The maximum timing error thereafter must not exceed 4.4ms
  - The timing accuracy is now determined not from the ppm error of the clock, but by generating interrupts at the correct intervals based on counting cycles of the MCU clock. This has a notional frequency of 32.768kHz with prescaler 2, allowing a timing granularity of approximately 0.061ms.

The above process is adopted by each node. Each node only transmits its own timing synchronisation message once it has successfully completed the above process.

Note however, a more stringent synchronisation requirement applies when the whole mesh is considered, as errors may be accumulated with each hop. For example, a node may receive messages from two parents which themselves might have worst case and opposite polarity timing drift , and the drift may accumulate for each level of mesh depth.

6.4.2 Re-Synchronisation

Re-synchronisation allows a single node to re-join an existing mesh. The only difference between Re-synchronisation and Synchronisation is that the mesh is already operating using channel hopping, so the node attempting to re-synchronise will listen on a single channel, and will have to wait for the mesh to transmit a

DCH on that channel. Consequently, it will usually take the node longer to find the first sync message on the DCH for re-synchronisation than for synchronisation. Once the node has received a first sync packet, it will be able to read the long frame index (0 to 127) from the payload, and will then be able to follow the mesh's hopping pattern, which it must do for the rest of the re-synchronisation process and all subsequent operation.

Re-synchronisation will be required when a node has dropped from the mesh, for example after a firmware upgrade, after a battery change, or after any other loss of synchronisation with the mesh.

6.5 Medium Access Control

6.5.1 Frame Sizes

The Frame sizes are calculated in HKD-17-0065-D Mesh Protocol Message Lengths [25]The sizes are shown in Table 14. The last two columns give the amount the frame could increase by without increasing the frame Time on Air. Refer section 5.3 for explanation.

Frame	Data Size (bytes)	Contingency Size (bytes)	Total Size (bytes)
Heartbeat	11	3	14
Data	22	1	23
Acknowledgement	10	3	13
SetAddress	10	3	13
Firmware Update Downlink	255	0	0
Firmware Update Uplink	12	1	13

Table 14: Frame sizes

6.5.2 Priorities

Fire, First Aid and PIR detection signals all need to be sent in the uplink. The RACH channels that we use for the uplink include contention where a signal from one source can be delayed by a signal from another source. There is a requirement that fire signals are not blocked or delayed by other signals. The MAC meets this requirement by supporting two completely independent RACH channels – P-RACH for fire signals and S-RACH for all other uplink traffic. This approach ensures that fire detection signals will not be blocked or delayed by other signals.

6.5.3 Resilience to Transmission Losses

EN54 requires that the system continues to detect fires and activate sounders and does not raise faults when the radio is periodically blocked by interfering signals.

Each channel type incorporates resilience to blocking in different ways.

Channel Type	Resilience to radio blocking

Random Access Channel	Acknowledged data transfer with retransmission on failed transfer. Retransmissions use path diversity (by using either primary or secondary parent) and frequency agility (channel hopping).
Downlink Common Channel	This channel broadcasts messages to multiple nodes at the same time so messages cannot be acknowledged. Critical messages like Output messages are repeated a number of times to provide resilience against transmission losses, where such retransmissions use frequency agility (channel hopping) and time separation (slot selection).
Dedicated Channel	Messages repeat every 193.75 seconds, being the long frame duration. The messages are not acknowledged. The transmissions use frequency agility (channel hopping) such that all the available RF channels are used within the hopping sequence.

6.5.4 Channels

Calculations for transfer rates are given in Appendix E.

Name	Direction	Ack / Unack	Dedicated / Shared	Number of Slots per second	Information Flow
P-RACH	Uplink	Ack	Shared	2.7	Fire Detection
S-RACH	Uplink	Ack	Shared	2.7	First Aid Detection PIR Detection
DL-CCH	Downlink	Unack	Shared	0.7	Alarm Sounding
DCH	Uplink and Downlink	Unack	Dedicated	2.7	Heartbeat / Synchronisation

6.6 Procedures

6.6.1 Link Check

The options for periodic checking of links are discussed in HKD-17-0017-D Link Check Options [11]. The approach implemented is described in Figure 11.

Once RUs are synchronised to the TDM structure then this is used to check links between RUs. Every RU transmits periodically once per long frame in the slot allocated to it in the TDM structure. All the parents and children of this RU know they are parents / children and also know when the RU will transmit its Heartbeat packet. They use this knowledge to wake up and check whether they receive the Heartbeat and also the RSSI if the reception is successful.

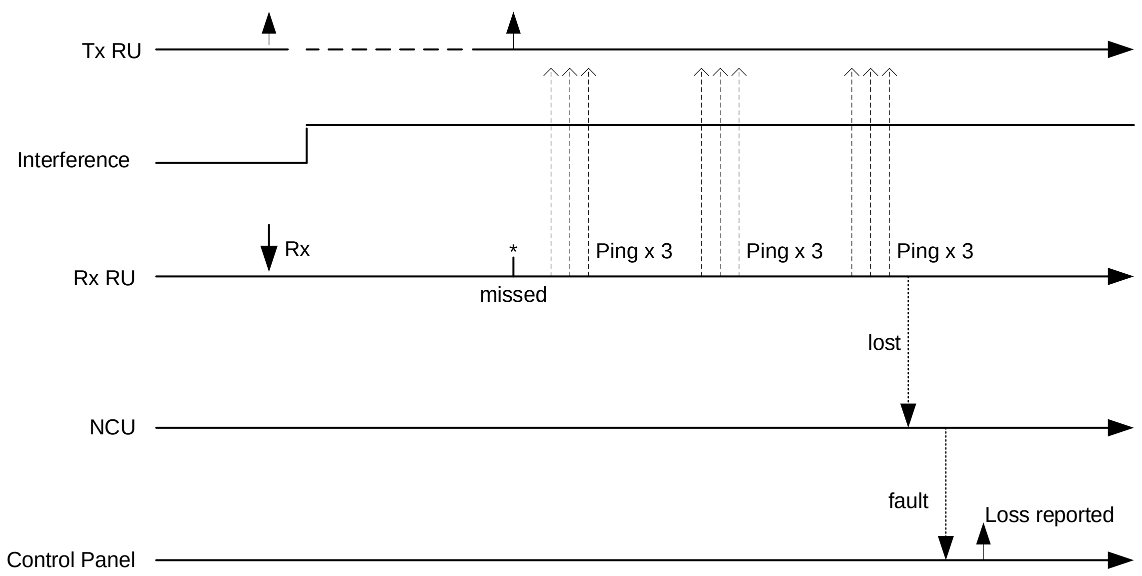


Figure 11: Link Failure Detection

6.6.2 Random Access

The random access approach is taken from WirelessHART, BS EN 62591:2016 [1] § 6.4.4.4. This uses Slotted ALOHA which is an industry standard approach for Random Access Channels in radio systems.

RUs are allocated shared slots in the TDM structure for Random access. These slots are shared so it is possible for more than one RU to attempt to access the same slot at the same time. If this occurs it is a collision and could require either or both packets to be retransmitted.

An acknowledge mechanism is used to check if packets have been transferred correctly. If the acknowledgement is not received by the source this is an indication that the data packet needs to be retransmitted. When this happens the sender waits a back-off period and then retransmits the packet.

To reduce the probability of repeated collisions, source devices use random back-off delay whenever an Ack is not received.

The RU maintains two variables:

- Backoff exponent (BackoffExp)
- Backoff counter (BackoffCounter)

These are both initialised to zero. When a transaction fails, BackoffExp is increemented and the random back-off period (counted in slots in the associated channel) will be calculated based on BackoffExp. For each unsuccessful attempt by the source device, BackoffExp is incremented and a random number is selected from the sets shown in Table 15. The value of BackoffExp will not exceed ACK_MAX_BACKOFF_EXPONENT.

Table 15 shows the back-off sets for BackoffExp values from 1 to 8.

BackoffExp	Set of possible values for BackoffCounter
1	{ 1 → 7)
2	{ 1 → 15 }
3	{ 1 → 23 }
4	{ 1 → 47 }
5	{ 1 → 63 }
6	{ 1 → 95 }
7	{ 1 → 127 }
8	{ 1 → 255 }

Table 15: BackoffCounter Selection Sets

The Backoff counter and Backoff exponent are maintained separately for each neighbour and separately for RACH1 and RACH2 channels.

Parameter	Description	Required Value
-	The minimum value of the Backoff Exponent (BE)	1
ACK_MAX_BACKOFF_EXPONENT	The maximum value of the BE	8

Table 16: BackoffExp Range

6.6.3 Channel Hopping

The channel hopping algorithm is defined in HKD-17-0057-D Channel Hopping Algorithm [24].

6.6.4 System ID

All MAC frames include a System ID. This is a 32 bit value that corresponds to the NCU Serial Number and forms part of every message. On message receipt the System ID can be checked to determine if the message is for the expected system.

This is the mechanism used to discriminate between messages generated by the expected system, and other system messages or spurious messages. It is applicable to the NCU and to all RBUs in the network.

This means that any node in the network is able to decode messages from other nodes in the network. Messages for other networks will be discarded because they were have a different System ID. This 32 bit field gives a probability of false detection of 1 in 4 billion (in the absence of any bit error corruption within the System ID field).

6.7 Protocol Data Units

This section describes the messages and parameters used in the Cygnus 2 MAC layer. Any messages received with other message types or invalid parameters should be ignored.

6.7.1 Messages

This section contains descriptions of all MAC layer frames.

Frame Type	Name	RACH	ACK	DL-CCH	DCH
0	Heartbeat	No	No	No	Yes
1	Data	Yes	No	Yes	No
2	Acknowledgement	No	Yes	No	No
3	SetAddress	No	No	No	No
4	Firmware	No	No	Yes	No
5	Test	Yes	No	No	No

Table 17: MAC Layer Frames

Heartbeat

This frame is transmitted periodically by each RU in the system. This frame is only transmitted on the DCH channel.

It is used by RUs for the following purposes:

- To detect other RUs when performing neighbour scan (e.g. to join network)
- To acquire and maintain slot and super-frame synchronisation
- For link check
- In the Mesh Formation process to identify their rank, and to select parents of equal rank
- To signal their number of children, and the number of children or their Primary Tracking node, for use in selecting suitable parent nodes and for load balancing
- When joining an existing mesh to discover what state (encompassing descriptors such as mode, stage) the rest of the network is in.

The slot index is derived from the address of the node transmitting using the formula given in section 6.1. When a heartbeat is received the originator can be derived from the short frame index and the slot index contained in the heartbeat.

The Routing Information (see section 7.2.1) is carried in the MAC Payload field.

The frame structure is shown in Figure 12.

Frame Type	Slot Index	MAC Payload	System ID

Figure 12: Heartbeat Frame Format

Data

This frame is used to transmit data between RUs. This frame is only transferred over RACH and DL-CCH channels. It is used for the following types of messages:

- Alarm Signals
- Fault Signals
- Route Add Messages
- Route Drop Messages
- Command Messages
- Status Indication Messages

- Output Signals

The frame structure is shown in Figure 13

Frame Type	MAC Destination Address	MAC Source Address	MAC Payload	System ID

Figure 13: Data Frame Format

Acknowledgement

This frame is used to acknowledge reception of data within a slot. All messages sent to non-broadcast addresses are acknowledged.

The frame structure is shown in Figure 14.

Frame Type	MAC Destination Address	MAC Source Address	System ID

Figure 14: Acknowledgment Frame Format

Test

This frame is used to send packets of test data from an RU / NCU to other RUs. It is a non-standard message with address fields removed to increase the space available for the test data block.

The frame structure is shown in Figure 15.

Frame Type	MAC Source Address	Test Payload	System ID

Figure 15: Test Frame Format

6.7.2 Parameters

Address

The address of units for communication over the mesh.

Number of bits used: 12

Bit 9 – bit 0 Unit Address

Bit 11 – bit 10 reserved – set to 0.

Examples of addresses are given below:

Address of unit	0	0	U	U	U	U	U	U	U	U	U	U

Frame Type

Number of bits used: 4

Frame Type Parameter Values defined in Table 17

MAC Destination Address

The destination address for a single hop transfer on the RACH channel.

Downlink messages do not use MAC layer addressing so this field should be set to 0xFFF.

Number of bits used: 12

Bit 9 – bit 0 Unit Address

Bit 11 – bit 10 Broadcast bits

Examples of addresses are given below:

Addressing a single unit (used for RACH)	0	0	U	U	U	U	U	U	U	U	U	U
Broadcast (used for Downlink)	1	1	1	1	1	1	1	1	1	1	1	1

MAC Payload

The MAC payload carries network layer data depending on the frame type. The Heartbeat frame carries Routing Information data. The Data frame carries NPDU data.

MAC Source Address

The source address for a single hop transfer on the RACH channel.

Downlink messages do not use MAC layer addressing so this field should be set to 0xFFF.

Number of bits used: 12

Bit 9 – bit 0 Unit Address

Bit 11 – bit 10 Broadcast bits

Examples of addresses are given below:

Addressing a single unit (used for RACH)	0	0	U	U	U	U	U	U	U	U	U	U
Broadcast (used for Downlink)	1	1	1	1	1	1	1	1	1	1	1	1

Serial Number

The Serial Number of the RBU.

Number of bits used: 32

Slot Index

The current slot number in the TDM structure. This consists of the index in the short-frame, the index in the long-frame and the index in the super-frame. This is used for frame synchronisation both when an RU joins for the first time and to maintain synchronisation during normal operation.

Number of bits used: 17

Bit 2 – bit 0 DCH index within Short-frame (in the range from 0 to 3), corresponding to slots 0 to 3 within the short frame. (The MSB of this field is currently not used, but provides expansion to support up to 8 DCH slots.)

Bit 10 – bit 3 Short-frame index within long-frame (in the range from 0 to 127)

Bit 16 – bit 11 Long-frame index within super-frame (in the range from 0 to 63)

SystemID

The System Identity field. This would normally be set to the ID number of the NCU. It is used throughout the system so that messages from other systems are not unintentionally accepted.

Number of bits used: 32

Test Payload

Payload of 13 bytes used exclusively in test mode messages. There are no restrictions on the content of the test payload.

Number of bits used: 104

6.8 Configurable Parameters

Parameter	Description
operationMode	Normal or Neighbour scan
nodeAddress	Address of this node (0-511)
neighbourList	List of neighbour RUs for link checking
isMaster	Flag for master –timing adjustment is inhibited for master

Table 18: MAC Configurable Parameters

7 NETWORK / RRC LAYER

This layer sits above the MAC layer in the protocol stack. It performs the following functions.

Mesh Establishment and Maintenance

When the network is started each node determines which parent nodes to connect to in order to form the mesh.

This is achieved by scanning for the Heartbeat messages from the neighbouring nodes and selecting the best node to join. When the node joins a parent it becomes part of the mesh and starts the regular transmission of its Heartbeat message. Where possible, each node selects two active parent nodes (the primary and secondary parents) to provide resilience against failure of a single node or link. Each node may record alternative candidate parents during this process in order to speed up mesh reconfiguration activities in the event of the future loss of either parent.

The mesh is built up from the NCU. Initially the NCU is the only node transmitting a Heartbeat. The other nodes that are in range then join the mesh with the NCU as a parent and start transmitting their Heartbeats. This process continues until all the nodes are connected to the network.

Figure 16 shows the links that are monitored by a node in the mesh. Ideally each node monitors at least two parent nodes. However this may not be possible if the parent is the NCU or if the two nodes are not available.

Not all nodes will have children. Nodes on the edges of the mesh may not have any child nodes. These are called 'leaf' nodes.

Mesh Forming and Healing is described in more detail in HKD-17-0329-D Forming and Healing [28].

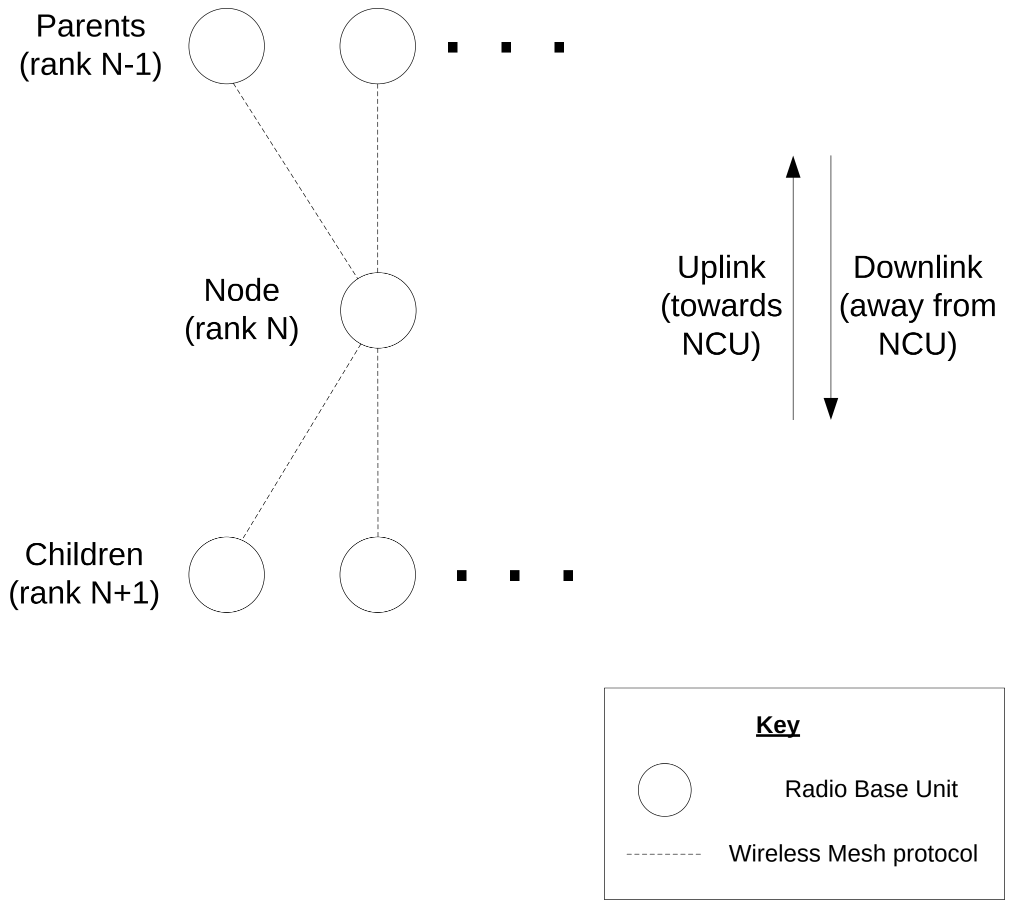


Figure 16: Diagram of the monitored links between a node and its parents and children

Link Check

This uses the link check mechanism provided by the MAC layer. This layer maintains lists of the parent and child nodes and selects these links to be checked.

The parent nodes are identified by scanning neighbourhood nodes and selecting parents (based on rank and power). This occurs when the node joins the network and periodically after joining.

A node is informed that it has a child by messages received from the child. If the node receives a routeAdd message it adds the sender to its list of child nodes. Conversely, if it receives a routeDrop message it removes the sender from the list of child nodes.

Logon / Status Indication

The status indication is a message sent from each node to the NCU. It is sent when the node joins the network.

When the node joins for the first time this message provides the following:

- An indication to the CP that the node has joined the network
- Details of the device connected to the Radio Base Unit

- The current state of the joining RBU, which will typically be 'Active.'

Routing

This function is used for routing packets across multiple hops in the mesh. Different approaches are used for the uplink and downlink:

For the Uplink, messages are sent on one of the RACH channels. Each node maintains a list of parent nodes. Messages are sent in the uplink direction using the individual address of the next hop in the uplink direction. The node cycles through the set of parents to provide resilience against link/node failure.

For the Downlink, messages are sent on the DL-CCH channel. All packets are always distributed to all the nodes in the mesh. At each node the destination address in the packet is compared to the node address. The following types of addressing are supported:

- Individual addressing
- Zone addressing
- Global addressing

7.1 Procedures

7.1.1 Mesh Forming

The mesh forming process follows the design detailed in [28]; see also the mesh forming scenarios document. [13]

7.1.2 Mesh Healing

The mesh healing process follows the design detailed in [28]; see also the scenarios in the Mesh Healing Scenarios document [14].

7.1.3 Link Check

Each node monitors Heartbeat messages from all the nodes in its list of parent and child nodes. This uses the link check procedure described in section 6.6.1. This is repeated for each cycle of the Heartbeat.

If the node fails to receive a valid Heartbeat from the child a series of 'ping' messages are sent to the child. If the child acknowledges one of the pings the link is maintained. If all pings go unanswered, the child is dropped and the control panel is informed.

7.1.4 Logon / Status Indication

This is an indication message sent from each node to the NCU.

The status indication is sent from the node when the node joins the network to inform the NCU that a new node has joined. The message contains the Mesh status of the RU.

7.1.5 Routing

Different routing approaches are used in the uplink and downlink directions.

Uplink

The approach for routing is based on the RPL[12] protocol. This is an established routing protocol designed for low power networks. We support the following traffic flows from RPL:

- Multipoint-to-point – traffic flow from network nodes to the central control point

In the CygnusII system this corresponds to the following:

- Uplink traffic – messages transferred from RUs to the NCU.

Each node maintains a lists of parent nodes that are a single hop closer to the root. To transfer each uplink message, the node selects The primary parent and transfers the packet to it using its individual address. Repeated messages are alternately addressed to the secondary and primary parents to give resilience against transmission failure.

If a node only has a single parent then it is not able to cycle through different destinations. This will always be the case for rank 1 nodes which only have the NCU as a parent.

Downlink

In the downlink direction each message is sent to all nodes in the mesh. The process of sending a message starts at the NCU and uses the mechanism described in the DL-CCH section 6.2.2 to propagate the message to all the nodes.

When the packet arrives at a node it checks the destination address in the network / RRC layer to determine if the packet is to be forwarded to the application. The following types of addressing are supported:

Addressing a single unit

The NCU transmits the packet and it is propagated to all the RUs in the mesh. For this case, the destination address contains the **individual address** of the intended destination. If this matches the unit address then the packet is passed to the application.

Addressing all units in a zone

The NCU transmits the packet and it is propagated to all the RUs in the mesh. For this case, the destination address contains the **zone address**. If this unit is part of that zone then the packet is passed to the application.

Addressing all units

The NCU transmits the packet and it is propagated to all the RUs in the mesh. For this case, the destination address contains the **broadcast address**. The packet is passed to the application in all units.

7.1.6 Frequency Adaptation

Frequency adaptation is the term used to describe the ability of the mesh system or of mesh nodes within a mesh system to identify and avoid channels that are proving unreliable, e.g. due to other local devices using the same channels.

Frequency adaptation would add considerable complexity to the mesh protocol design, and to the channel hopping algorithm. It could also have significant impact on the degree of testing required to demonstrate compatibility with EN54, as tests would perhaps need to cover a range of different channel availability scenarios.

Since we have both path and channel diversity schemes in place, we have elected to not implement frequency adaptation at this stage.

7.1.7 Encryption

The Data and Firmware frames encrypt their data payloads using 3DES. This uses blocks of 8 bytes.

Encryption is described in more detail in HKD-17-0045-OP Cygnus 2 Encryption [27].

7.2 Protocol Data Units

This section describes the messages and parameters used in the Cygnus 2 Network / RRC layer. Any messages received with other message types or invalid parameters should be ignored.

7.2.1 Messages

This section contains descriptions of all the Network / RRC layer messages.

NPDU

This message is sent in the payload of a data frame. It includes the parameters required to transport the packet across the mesh.

This includes a source and destination address. The network layer transfers messages across the mesh so these refer to the address of the originator and final destination nodes. They are different to the MAC source address and MAC destination addresses in the MAC layer which are source and destination of a single hop.

The Network Payload is padded to a multiple of 8 bytes (required for 3DES encryption) and encrypted.

The message structure is shown in Figure 17.

Hop Count	Destination Address	Source Address	Network Payload

Figure 17: NPDU Message Structure

Routing Information

This message is sent in the payload of a Heartbeat frame.

The message structure is shown in Figure 18.

State	Rank	NCI	NCPTNI

Figure 18: Routing Information Message Structure

7.2.2 Parameters

Destination Address

The destination address for the packet in the mesh. This may be one hop away or multiple hops away. This should be unique in the system.

The address is composed of the following fields:

Number of bits used: 12

Bit 8 – bit 0 Unit Address

Bit 11 – bit 9 Broadcast bit

Examples of addresses are given below:

Addressing a single unit	0	0	0	U	U	U	U	U	U	U	U	U
Addressing all units	1	1	1	1	1	1	1	1	1	1	1	1

Hop Count

A count of the number of times the message has been retransmitted by nodes in the mesh. It is set to zero when the message is first transmitted and incremented for each hop.

Number of bits used: 8

Network Payload

The network payload carries application layer data.

Number of bits used: 64

State

This parameter signals which mode and state the mesh is in. It is used by RUs that are joining an existing mesh to discover what Mode and Stage the rest of the network is in so that it can behave accordingly. The meanings of each value of this are the same as those defined in Section 8.2.2 for the State parameter of the Application Layer..

Number of bits used: 4

Number of Children Index (NCI)

This parameter signals the number of children of the node. The number of children that a node can have is a configurable parameter. This parameter is a scaled index to indicate how close the node is to achieving its configured maximum number of children. The allocated 4 bits allow a range of 0→15, where 0 means that the node has no children and 15 means that it has its maximum allocation.

Number of bits used: 4

Number of Children of Primary Tracking Node Index (NCPTNI)

This parameter signals the number of children of the primary tracking node of the node. It is a scaled index, identical in operation to the NCI parameter that is defined above.

Number of bits used: 4

Rank

This is the number of hops from the root of the message sender. The NCU is Root so it has a rank of zero. The children of NCU have rank of 1 etc.

Number of bits used: 6

Source Address

The source address for the packet in the mesh. The format is the same as the Destination Address. This should be unique in the system.

Number of bits used: 12

7.3 Configurable Parameters

None

8 APPLICATION LAYER

8.1 Procedures

8.1.1 Alarm Detection

When a fire detector crosses one of its thresholds or a fire call point is pressed the Fire Signal is sent via the NCU to the CP.

Fire detectors include heat and smoke detectors.

When a non-fire related alarm is triggered (e.g. PIR) or a First Aid call point is pressed the Alarm Signal is sent via the NCU to the CP.

8.1.2 Alarm Sounding

If the CP wants to activate the outputs it triggers an Output Signal from the NCU. This will be globally addressed to all units. It contains a bit map of all activated outputs.

When the CP silences the alarm an Output Signal is sent from the NCU again. However this time audio outputs are inactive.

When the CP resets the alarm system all outputs are made inactive by sending an Output Signal with all outputs set to inactive.

8.1.3 Parameter Read / Write

The Read and Write commands can be used to read parameters from Remote Units or to write parameters to Remote Units. These commands use individual addressing.

These transactions use a pair of messages – a Command sent to the RU and a Response returned from the RU to the originator. Both command and response messages must have matching Transaction Id. This is incremented each time a new transaction is started.

When the RU receives a command it checks the message size and that all parameters are in range and discards invalid messages.

After performing the requested command, the RU sends a Response to the originator. When this arrives at the originator the Transaction Id and Read/Write values are checked.

If no response is received within a timeout period an error is passed to the application. If the response is received it is passed to the application.

Once the originator has sent a command it is not permitted to send another command until either of the following has occurred:

- A response has been received with the same transaction id
- The timeout expires.

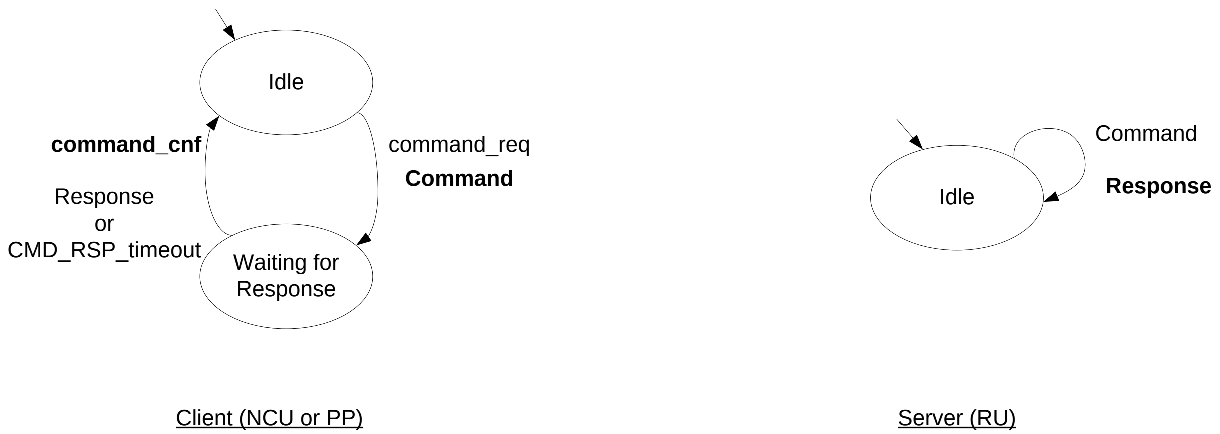


Figure 19: State Diagram for Parameter Read / Write

8.2 Protocol Data Units

This section describes the messages and parameters used in the Cygnus 2 application layer. Any messages received with other message types or invalid parameters should be ignored.

8.2.1 Messages

This section contains descriptions of all the Application layer messages.

Message Type	Message Name	Dir	Channel (Config)	Channel (Active)	Addressing
0	Fire Signal	Uplink	N/A	P-RACH	Individual
1	Alarm Signal	Uplink	N/A	S-RACH	Individual
2	Fault Signal	Uplink	N/A	S-RACH	Individual
3	Output Signal	Downlink	N/A	DL-CCH	Individual, Zone or Global
4	Command	Downlink	N/A	DL-CCH	Individual
5	Response	Uplink	N/A	S-RACH	Individual
6	Logon	Uplink	P-SACH	S-RACH	Individual
7	Status Indication	Uplink	N/A	S-SACH[4]	Individual
8	App Firmware	Downlink	N/A	DL-CCH	Individual, Zone or Global
9	Route Add	Uplink	S-RACH	S-RACH	Neighbour

[4] Note, the interval between S-SACH Access Slots will depend on whether the Status Indication is in response to an Individual, Zone or Global Status Request.

10	Route Add Response	Downlink	S-RACH	S-RACH	Neighbour
11	Route Drop[5]	Uplink	S-RACH	S-RACH	Neighbour
12	Test Mode	Downlink	N/A	S-RACH	Individual
13	Test Signal	Broadcast	N/A	N/A	Global
14	SetState	Downlink	N/A	DL-CCH	Global
15	Load Balance	Downlink	N/A	S-SACH	Neighbour
16	Load Balance Response	Uplink	N/A	RACH	Neighbour
17	Acknowledgement	Up/downlink	N/A	RACH	Neighbour
18	Heartbeat	Downlink	DCH	DCH	Global
19	RBU Disable	Downlink	N/A	DL-CCH	Global
20	Fault Status Signal	Uplink	N/A	RACH	Individual
21	Output State Request	Downlink	N/A	RACH	Neighbour
22	Output State	Uplink	N/A	RACH	Individual
23	Message Unknown	Internal Error Handling	N/A	N/A	Individual
24	Alarm Output State	Downlink	N/A	DLLCH	Global
25	Ping	Up/Downlink	NA	S-RACH	Neighbour
26	Battery Status	Uplink	N/A	S-RACH	Individual
27	Day/night Status	Downlink	N/A	DLCCH	Global
28	Zone Enable	Downlink	NA	DLCCH	Global

Table 19: Application Layer Messages

Fire Signal

This signal is sent from a radio unit to the NCU to communicate a change in the state of a single **fire related** detector (for example when detector exceeds a predefined threshold). The RU channel index is used to distinguish between multiple sensors in the same RU.

For example, this signal can be generated from the following component types:

- Smoke detector
- Heat detector

[5] Note, the Route Drop message is not currently used.

- Fire call point
- I/O unit input channel handling Fire

The message structure is shown in Figure 20

Message Type	RU Channel Index	Zone	Alarm Active	Sensor Value

Figure 20: Fire Signal Message Structure

Alarm Signal

This signal is used in a similar way to the Fire Signal. The difference is that the Fire Signal is used for fire related events and this signal is used for Non-fire related events.

This signal is sent from a radio unit to the NCU to communicate changes in the state of **non-fire related** detectors. The RU channel index is used to distinguish between multiple sensors in the same RU.

For example, this signal can be generated from the following component types:

- PIR detector
- First Aid call point
- I/O unit input channel handling non-Fire input

The message structure is shown in Figure 21.

Message Type	RU Channel Index	Zone	Alarm Active	Sensor Value

Figure 21: Alarm Signal Message Structure

Fault Signal

This signal is sent from a radio unit to the NCU to communicate a change in the status flags of the Radio Base Unit. Specific fault types are included for Detector, Beacon and Sounder devices.

The message structure is shown in Figure 22.

Message Type	Channel	Fault Active	Fault Type	Overall Fault

Figure 22: Fault Signal Message Structure

Output Signal

This signal is sent from the NCU to RBUs to control all the outputs on the RBU. This includes sounders, LEDs and beacons. The message can be used to control a single RBU or broadcast to control all the RBUs in the network.

This can be sent to all radio unit types.

The message structure is shown in Figure 23.

Message Type	Zone	Channel	Output Profile	Output Activated	Output Duration

Figure 23: Output Signal Message Structure

Alarm Output State

This signal sends the current alarm state of the control panel to the radio devices. All RBUs examine the state mask parameters and set their outputs to match the alarm state.

This can be sent to all radio unit types.

The message structure is shown in Figure 23.

Message Type	Silenceable Mask	Unsilenceable Mask	Delay Mask

Figure 24: Alarm Output State Message Structure

Command

This signal is sent from the NCU or the PP to an RBU. It is the first message in a COMMAND-RESPONSE transaction.

The Read / Write parameter is used to distinguish between commands to read a parameter value from the RU or to write a parameter value to the RU

The same Transaction Id is used for the COMMAND and RESPONSE messages. This is incremented for each transaction.

The message structure is shown in Figure 25.

Message Type	Parameter Type	Read / Write	Transaction ID	P1	P2	Parameter Value

Figure 25: Command Message Structure

Response

This signal is sent from an RBU in response to a Command message. It is the second message in a COMMAND-RESPONSE transaction. It is sent back to the originator of the Command message.

The Read / Write parameter is used to distinguish between commands to read a parameter value from the RU or to write a parameter value to the RU

The same Transaction Id is used for the COMMAND and RESPONSE messages. This is incremented for each transaction.

The message structure is shown in Figure 26.

Message Type	Parameter Type	Read / Write	Transaction ID	P1	P2	Parameter Value

Figure 26: Response Message Structure

Status Indication

This message is sent from an RU to the NCU for any change in mesh status.

The message structure is shown in Figure 27

Message Type	Primary Parent ID	Secondary Parent ID	RSSI Primary Parent	RSSI Secondary Parent	Rank	Event	Event Data	Overall Fault

Figure 27: Status Indication Message Structure

Route Add

This message is sent from an RU when it joins the network or re-joins. It is sent to a parent node. The request is either Accepted or Refused, as signalled in a Route Add Response message.

The message structure is shown in Figure 28.

Message Type	Rank	Is Primary	Zone

Figure 28: Route Add Message Structure

Route Drop

This message is sent from an RU to the NCU when the link check fails for an RU. When this is received, the NCU should send a message to the CP indicating a connection fault.

The message structure is shown in Figure 29.

Message Type

Figure 29: Route Drop Message Structure

Set State

This message is sent from the NCU to all the RBUs to signal when the mesh as a whole should adopt a specified State. (The term State covers system-wide behavioural descriptors including Mode, Stage and State, all of which have been used in the requirements definition and in subsequent design discussions).

The message structure is shown in Figure 30.

Message Type	State

Figure 30: Set State Message Structure

Route Add Response

This message is sent in response to a received Route Add message. If the Accepted flag is set to True, the sending node accepts parental responsibility over the child node, such as monitoring its DCH heartbeat signal and notifying the NCU if the heartbeat is not received or has degraded to an unacceptable SNR. The remaining fields pass current mesh status information to the joining node. The message is sent twice in order to pass all on the zone enablement bits. The first message passes the first 48 bits (Zone Upper Lower=0) and the second carries the last 48 bits (Zone Upper Lower=1).

The message structure is shown in Figure 31.

Message Type	Accepted	Day/Night	Global Delay Enable	Sound Level	Zone Enabled	Zone Lower Upper	Zone Word	Zone Half Word	Faults Enabled	Global Delay Override

Figure 31: Route Add Response Message Structure

Load Balance

This message is sent from an RU to one of its child nodes, to signal a request that the child node finds a different parent node. This process serves to free-up spaces in a parent node to accept different child nodes (some of which may have no alternatives for a parent node), and also promotes more even distribution of the battery life in different RBUs.

The message structure is shown in Figure 32.

Message Type

Figure 32: Load Balance Message Structure

Load Balance Response

This message is sent from an RU to one of its parent nodes in response to a Load Balance message. The response is Boolean, and with the Accepted flag set to either True (the node has swapped to a different parent), or False (the node has not swapped to another parent).

The message structure is shown in Figure 33.

Message Type	Accepted

Figure 33: Load Balance Response Message Structure

RBU Disable

This message is sent by the NCU to all RBUs, to request that one specified device is disabled. Disabled means that the device turns off until manually reset by the engineer. N.B. that this reset cannot be signalled over the mesh, because the device is disabled.

The message structure is shown in Figure 34.

RBU Disable

Message Type	Unit Address

Figure 34: Status Request Message Structure

Output State Request

This message is sent by the Primary Parent node to one of its children to request that the child responds with an Output State message, giving its last commanded output.

Message structure.

Output State Request

Message Type

Figure 35: Output State Request Message Structure

Output State

This message is sent by a child node to its Primary Parent in response to an Output State Request message. The returned value is the last commanded output that was accepted by the child node.

Message structure.

Message Type	Zone	Channel	Profile	Activated	Duration	Silenceable Mask	Unsilenceable Mask	Delay Mask

Figure 36: Output State Message Structure

Battery Status Message

The battery status message is sent by each radio board to the control panel so that the battery voltages can be reported.

Message structure.

Message Type	Primary Battery Voltage	Secondary Battery Voltage	Device Combination	Zone	Smoke Sensor Value	Heat Sensor Value	PIR Sensor Value

Battery Status Message Structure

Ping Message

The ping message is used by neighbouring nodes to verify the presence of a device when the heartbeat has been missed. It is used to maintain the parent/child link in noisy environments. An acknowledgement by the target device verifies its presence.

Message structure

Ping

Message Type

Ping Message Structure

8.2.2 Parameters

This section contains descriptions of all the parameters used in application layer messages.

Table 20 contains all the parameters on the RBU that can be read or written over the mesh.

P1 and P2 are additional parameters used to address parts of the RBU. Their use depends on the Parameter Type being read / written. If they are shown as 'unused' in the table below then they are still present in the message but they are set to zero. There is no advantage removing these parameters if they are not used because it does not reduce the size of the complete message. The size is limited by the encryption block size.

The width of the Value depends on the Parameter Type being read / written.

Value	Name	P1	P2	Number of bits for Value	Readable	Writeable
0	Analogue Value	RU Channel Index	Zone	8	Yes	No
1	Neighbour Information	Neighbour Type	Zone	24 Neighbour Index	Yes	No
2	Status Flags	unused	Zone	8	Yes	No
3	Device Combination	unused	Zone	8	Yes	No
4	Alarm Threshold	RU Channel Index	Zone	8 Day Value 8 Night Value	Yes	Yes
5	Pre-Alarm Threshold	RU Channel Index	Zone	8 Day Value 8 Night Value	Yes	Yes
6	Fault Threshold	RU Channel Index	Zone	8	Yes	Yes
7	Flash Rate	RU Channel Index	Zone	8 O/P Profile 8 Value	Yes	Yes

Value	Name	P1	P2	Number of bits for Value	Readable	Writeable
8	Tone Selection	RU Channel Index	Zone	8 O/P Profile 8 Value	Yes	Yes
9	RBU Serial Number	unused	Zone	32	Yes	No
10	Plugin Serial Number	RU Channel Index	Zone	32	Yes	No
11	RBU Enable	unused	Zone	8	Yes	Yes
12	Plugin Enable	RU Channel Index	Zone	8	Yes	Yes
13	Modulation Bandwidth	unused	unused	2	Yes	Yes
14	Spreading Factor	unused	unused	4	Yes	Yes
15	Frequency	unused	unused	4	Yes	Yes
16	Coding Rate	unused	unused	2	Yes	Yes
17	Tx Power	unused	unused	2	Yes	Yes
18	Test Mode	unused	unused	8	Yes	Yes
19	Plugin Test Mode	RU Channel Index	unused	8	Yes	Yes
20	Firmware Information	Firmware Index	Zone	21	Yes	No
21	Firmware Active Image	unused	Zone	1	Yes	Yes
22	Reboot	unused	Zone	0	No	Yes
23	SVI	SVI Register	Zone	8	Yes	Yes
24	RBU Disable	unused	Zone	0	No	Yes
25	Low Tx Power setting	unused	Zone	8	Yes	Yes
26	High Tx Power Setting	unused	Zone	8	Yes	Yes
27	Output State Request	unused	unused	16	Yes	No
28	Programmed Zone	unused	Zone	12	Yes	Yes
29	CRC Information	Firmware Index	Zone	16	Yes	No
30	PIR Reset	unused	Zone	0	No	Yes
31	EEPROM Information	EEPROM index	Zone	32	Yes	Yes
32	Fault Type	RU Channel Index	Zone	8	Yes	No
33	Mesh Status	unused	Zone	0	Yes	No
34	Plugin Indicator LED	unused	Zone	1	Yes	Yes
35	Plugin ID Number	unused	Zone	16	Yes	Yes

Value	Name	P1	P2	Number of bits for Value	Readable	Writeable
36	Plugin Firmware Info	unused	Zone	0	Yes	No
37	Set Day/Night	unused	Zone	1	Yes	Yes
38	Alarm Acknowledge	unused	Zone	0	No	Yes
39	Evacuate	unused	Zone	0	No	Yes
40	Global Delay Enable	unused	Zone	1	Yes	Yes
41	Enable Disable	Device, channel or zone	Channel or zone number	1	Yes	Yes
42	Alarm Reset	unused	Zone	0	No	Yes
43	Sound Level	unused	Zone	2	Yes	Yes
44	Test One Shot	unused	Zone	1	No	Yes
45	Confirm	unused	Zone	4	No	Yes
46	Alarm Configuration	channel	Zone	6	Yes	Yes
47	Alarm Option Flags	channel	Zone	3	Yes	Yes
48	Alarm Delays	channel	Zone	32	Yes	Yes
49	Channel Flags	channel	Zone	6	Yes	Yes
50	Verify Outputs	unused	Zone	1	No	Yes
51	Set Max Rank	unused	Zone	32	Yes	Yes
52	200 Hour Test	channel	Zone	1	No	Yes
53	Firmware Check	unused	Zone	32	No	Yes
54	Local Delay Enable	channel	Zone	32	Yes	Yes
55	Set Global Delays	channel	Zone	32	Yes	Yes
56	Global Delay Override	unused	Zone	1	Yes	Yes
57	Battery Status Request	unused	Zone	0	No	Yes
58	Global Delays Combined	unused	Zone	32	No	Yes
59	Plugin Detector Type	unused	Zone	0	Yes	No
60	Plugin Type & Class	unused	Zone	0	Yes	No
61	Device Scan	unused	Zone	0	No	Yes
62 – 255	Not used					

Table 20: Parameter Type Values

Alarm Threshold

This parameter carries the sensor analogue value alarm threshold (See **Error! Reference source not found.**).

Number of bits used: 8

Analogue Value

This parameter value carries the analogue value read from the sensor. The range of values depends on the type of sensor being read.

Number of bits used: 8

Averaged SNR of Primary Parent

This parameter signals the averaged SNR of the primary parent of the node.

Number of bits used: 6

Averaged SNR of Secondary Parent

This parameter signals the averaged SNR of the secondary parent of the node.

Number of bits used: 6

Beacon Fault

Fault codes for Beacon devices. Included in the Fault Signal message.

Number of bits used: 4

Value	Description
0	No Error
1	Type/Class Mismatch
2	Device ID/Serial Mismatch
3	Beacon LED Faulty (no light)
4-15	Spare

Table 21: Beacon Fault Values

Block Count

This parameter contains a firmware block number.

Number of bits used: 14

Coding Rate

The channel coding rate used by the LoRa transceiver

Number of bits used: 2

Value	Description
0	4/5
1	4/6
2	4/7
3	4/8

Table 22: Coding Rate Parameter Values

Detector Fault

Fault codes for detector devices. Included in the Fault Signal message.

Number of bits used: 4

Value	Description
0	No Error
1	Type/Class Mismatch
2	Device ID/Serial Mismatch
3	Faulty Sensor
4	Dirty Sensor
5	Faulty and Dirty Sensor
6	Internal Fault
7-15	Spare

Table 23: Detector Fault Values

CRC Information

This parameter reads the CRC of the firmware on a remote device. It can address the current firmware or the backup firmware using the Firmware Index parameter in the P1 field.

Number of bits used: 16

Device Combination

This parameter value describes the collection of devices that are fitted on a given Remote Unit. Table 24 contains the list of device types that can be fitted to an RU.

Device	Direction

Smoke detector	Input
Heat detector type A1R	Input
Heat detector type B	Input
Smoke + Heat detector type A1R	Input
Smoke + PIR detector	Input
PIR detector	Input
Fire call point	Input
First Aid call point	Input
Sounder	Output
Beacon W-2.4-7.5	Output
Beacon W-3.1-11.3	Output
Beacon C-3-8.9	Output
Beacon C-3-15	Output
Visual Indicator (not EN54)	Output
Remote Indicator	Output
IO unit (2 inputs + 2 outputs)	Input and Output

Table 24: List of RU Devices

Any RU can be fitted with a number of devices in Table 24 in specific combinations. The list of supported combinations is shown in Table 25.

Number of bits used: 8

Value	Description	Requirements
0	No devices fitted (repeater)	RB5.5, RB5.6
1	Smoke detector	S5.4
2	Heat detector type A1R	S5.5
3	Heat detector type B	S5.5
4	Smoke and heat detector type A1R	S5.6
5	Smoke and PIR detector	S5.7
6	Beacon W-2.4-7.5	S5.8, S5.9, S5.10, S5.11, B5.1
7	Beacon W-3.1-11.3	S5.8, S5.9, S5.10, S5.11, B5.2
8	Beacon C-3-8.9	S5.8, S5.9, S5.10, S5.11, B5.3
9	Beacon C-3-15	S5.8, S5.9, S5.10, S5.11, B5.4
10	Remote Indicator	RB5.19
11	Sounder	S5.14
12	Sounder + Smoke detector	S5.4, S5.14
13	Sounder + Heat detector type A1R	S5.5, S5.14

Value	Description	Requirements
14	Sounder + Heat detector type B	S5.5, S5.14
15	Sounder + Smoke and heat detector type A1R	S5.6, S5.14
16	Sounder + Smoke and PIR detector	S5.7, S5.14
17	Sounder + Beacon W-2.4-7.5	S5.8, S5.9, S5.10, S5.11, S5.14, B5.1
18	Sounder + Beacon W-3.1-11.3	S5.8, S5.9, S5.10, S5.11, S5.14, B5.2
19	Sounder + Beacon C-3-8.9	S5.8, S5.9, S5.10, S5.11, S5.14, B5.3
20	Sounder + Beacon C-3-15	S5.8, S5.9, S5.10, S5.11, S5.14, B5.4
21	Sounder and visual indicator (not EN54)	S5.18
22	Sounder and visual indicator (not EN54) + Smoke detector	S5.4, S5.18
23	Sounder and visual indicator (not EN54) + Heat detector type A1R	S5.5, S5.18
24	Sounder and visual indicator (not EN54) + Heat detector type B	S5.5, S5.18
25	Sounder and visual indicator (not EN54) + Smoke and heat detector type A1R	S5.6, S5.18
26	Sounder and visual indicator (not EN54) + Smoke and PIR detector	S5.7, S5.18
27	Fire call point	S5.12
28	IO unit (2 inputs + 2 outputs)	S5.15
29	Construction site fire combination 1 (fire call point, sounder)	TBD
30	Construction site fire combination 2 (fire call point, sounder, visual indicator)	TBD
31	Construction site fire combination 3 (fire call point, PIR detector, sounder and visual indicator)	S5.20
32	Construction site first aid combination (first aid call point, sounder)	TBD
33	Construction site fire and first aid combination 1 (fire call point, first aid call point, sounder and visual indicator)	TBD
34	Construction site fire and first aid combination 2 (fire call point, first aid call point, PIR detector, sounder and visual indicator)	S5.21
35	Construction site smoke & heat detector with 85dBA sounder	TBD
36	Fire manual call point with radio base	S5.12
37	First aid manual call point (head only)	S5.12

Value	Description	Requirements
38	Construction site fire alarm call point with 85dBA Sounder & PIR	TBD
39	Construction site first aid alarm with 85dBA Sounder & PIR	TBD
40	Construction site smoke & heat detector with 85dBA sounder & PIR	TBD
41	Repeater	TBD
41 – 255	Unused	

Table 25: Device Combination Parameter Values

EEPROM Information

Each RBU has 32 words of non-volatile memory, reserved for future expansion, that are accessible remotely. This parameter provides read and write access to a reserved word which is addressed using the EEPROM Index value in the P1 field.

Number of bits used: 32

EEPROM Index

Used with the EEPROM Information command to address one of 32 reserved non-volatile memory locations on a remote device. It has a range of 0 to 31.

Number of bits used: 8

Enable

This parameter is used to enable / disable an RBU or a specific point.

Number of bits used: 8

Value	Description
0	Disabled
1	Enabled
2 – 255	Not used

Table 26: Enable Parameter Values

Fault Address

This parameter is only relevant if the Link Fault bit in the Fault Map is set. It contains the address of the link that has failed.

If no link faults are present this should be set to 0x000

Number of bits used: 12

Fault Threshold

This parameter carries the sensor analogue value fault threshold.

Number of bits used: 8

Fault Type

This parameter is used to read a fault code from a unit whose fault bit is set in the fault status report.

Number of bits used: 6

Value	Description
0	No Error
1	Type/Class Mismatch
2	Device ID/Serial Mismatch
3	Faulty Sensor
4	Dirty Sensor
5	Faulty and Dirty Sensor
6	Internal Fault
7	Sounder Faulty (Sound fault detected)
8	Beacon LED Faulty (no light)
9	Input Short Circuit Fault
10	Input Open Circuit Fault
11	Output Fault
12	Installation Tamper Fault (case / base removed from wall/ceiling)
13	Dismantle Tamper Fault (case opened / head removed from base)
14	Low Battery
15	Battery Fault

Firmware Block

This is a single block of firmware.

Number of bits used: 96

Firmware Index

Used by the Firmware Information command and the CRC Information command to identify which firmware image they wish to address. The CRC Information command only implements the RBU Main and RBU Backup images.

Number of bits used: 4

Value	Description
0	RBU Main Image
1	RBU Backup Image
2	External Interface-1 device (Head)
3	External Interface-2 device (Reserved)
4	External Interface-3 device (Reserved)
5	Internal Interface-1 device (I2C)
6	Internal Interface-2 device (Reserved)
7	Internal Interface-3device (Reserved)
8-15	Not Used

Table 27: Firmware Index Values

Firmware Information

A command to remotely read the firmware version of an application image stored in flash memory. One of several application images can be queried using the Firmware Index value in P1.

Number of bits used: 21

Bits 14→20 = Major (0 to 99)

Bits 7→13 = Minor (0 to 99)

Bits 0→6 = Revision (0 to 99)

Flash Rate

This parameter value carries the flash rate control for beacon or visual indicator. The range of supported values is shown in Table 28.

Number of bits used: 6

Value	Flash Rate / Hz	Requirements
0	0.5	B5.16
1	1	B5.16
2 – 63	Reserved	

Table 28: Flash Rate Parameter Values

Frequency

The frequency of the channel used for the LoRa transceiver. The value transferred is N. The centre frequency can be derived from N using the formula below:

Modulation BW	Centre Frequencies
500kHz	865.60 MHz + N*600 kHz, where N = {0,1,2,3}
250kHz	865.20 MHz + N*300 kHz, where N = {0,1,…,8,9}
125kHz	865.10 MHz + N*200 kHz, where N = {0,1,…,13,14}

Number of bits used: 4

Heat Sensor Value

The analogue value read from a heat sensor.

Number of bits used: 7

Image CRC

This parameter contains a CRC of the firmware image used to check integrity.

Number of bits used: 16

Is Primary

This parameter is used by the Route Add message. When a device sends this message to a candidate parent, this bit is set if the parent is to be the primary parent.

Number of bits used: 1

Last Commanded Fire

The Fire Profile output state that was last applied in a RBU.

Number of bits used: 8

Last Commanded First Aid

The First Aid Profile output state that was last applied in a RBU.

Number of bits used: 8

Last Commanded PIR

The PIR Profile output state that was last applied in a RBU.

Number of bits used: 8

Last Commanded Test

The Test Profile output state that was last applied in a RBU.

Number of bits used: 8

Last Commanded Silent Test

The Silent Test Profile output state that was last applied in a RBU.

Number of bits used: 8

Message Type

See Table 19

Number of bits used: 4

Modulation Bandwidth

The modulation bandwidth used for LoRa transceiver.

Number of bits used: 2

Value	Description
0	125 KHz
1	250 KHz
2	500 KHz
3	not used

Table 29: Modulation Bandwidth Parameter Values

Neighbour Index

This parameter is used to distinguish between multiple neighbours (parents or children) that are monitored by the node in the mesh.

This approach supports up to 256 parents and children per RU

Number of bits used: 8

Neighbour Information

A collection of parameters regarding parent / child nodes that are currently monitored by the RRC layer of a node in the network.

Number of bits used: 24

Bit 11 – bit 0 Address

Bit 15 – bit 12 unused (set to 0)

Bit 23 – bit 16 SNR

Neighbour Type

Identifier for neighbour type.

Number of bits used: 1

Value	Description
0	Parent
1	Child

Table 30: Neighbour Type Parameter Values

Number of Blocks

This parameter contains the number of firmware blocks in an image being downloaded.

Number of bits used: 14

Number of Blocks Outstanding

This parameter contains the number of firmware blocks not yet received by a given node.

Number of bits used: 4

Number of Children

This parameter contains the number of children of the node.

Number of bits used: 6

Number of Children of Primary Tracking Node

This parameter contains the number of children of the primary tracking node of the node.

Number of bits used: 6

Number of Parents

This parameter contains the number of active parents for the node.

Number of bits used: 2

Number of Tracking Nodes

This parameter contains the number of tracking nodes being used by the node.

Number of bits used: 2

Output Duration

Part of the Output Signal payload, this value sets the duration for which the outputs should be activated.

Number of bits used: 4

0000 - Activated permanently

0001 – Activated for 5 seconds

0010 – Activated for 10 seconds

0011 – Activated for 15 seconds

0100 – Activated for 20 seconds

Output Profile

Number of bits used: 4

Value	Description
0	Fire
1	First Aid
2	Evacuation
3	Security
4	General
5	Fault
6	Routing Ack
7	Test
8	Silent
9 – 15	Not used

Table 31: Output Profile Parameter Values

Outputs Activated

This parameter controls which outputs are to be activated. It consists of a bitmap of all supported output types. Use a bit value of 0 for Inactive and 1 for Active.

When an RU receives this parameter it should activate its outputs accordingly and ignore any bits corresponding to outputs that it does not support.

Number of bits used: 16

Bit Id	Output
Bit 0	Sounder
Bit 1	Beacon W
Bit 2	Beacon C
Bit 3	Visual Indicator (Not EN54)
Bit 4	Remote Indicator
Bit 5	Indicator LEDs
Bit 6	Status LEDs
Bit 7	IO Unit Output 1
Bit 8	IO Unit Output 2
Bit 9 - 15	Not Used

Example values of the Outputs Activated parameter are given below:

All outputs activated	1	1	1	1	1	1	1	1
All outputs except sounders activated	1	1	1	1	1	1	1	0
All outputs inactive	0	0	0	0	0	0	0	0

Output State Request

This parameter prompts a node on the network to report the value of its outputs. Note that the actual value that is returned is the last commanded value that the node acted upon.

Number of bits used: 16

Outstanding Block

This parameter contains the count of the smallest of the set of firmware blocks still outstanding at a given node.

Number of bits used: 16

P1

A parameter depends on the Parameter Type. This is described further in Table 20.

Number of bits used: 8

P2

A parameter depends on the Parameter Type. This is described further in Table 20.

Number of bits used: 8

Parameter Type

This is used to identify parameters on the RBU that can be read or written over the mesh.

Parameter Type values are defined in Table 20.

Number of bits used: 5

Parameter Value

This parameter carries the value of the parameter read or written.

Refer to Table 20 for the number of bits used for the parameter value.

Pre-Alarm Threshold

This parameter carries the sensor analogue value pre-alarm threshold (See **Error! Reference source not found.**).

Number of bits used: 8

PIR Reset

This parameter commands a remote unit to reset its PIR device.

Number of bits used: 0

PIR Sensor Value

The analogue value read from a PIR sensor.

Number of bits used: 1

Rank

This parameter contains the rank of node.

Number of bits used: 6

Read / Write

This parameter is used to select a command to read a parameter from an RU or a command to write a parameter to an RU.

Number of bits used: 1

Value	Description
0	Read
1	Write

Table 32: Read / Write Parameter Values

RU Channel Index

This parameter is used to distinguish between multiple components (sensors, IO ports and outputs) fitted on the same Radio Base Unit. The list of channel index values is given below.

Value	Description
0	None
1	Smoke
2	Heat B
3	CO
4	PIR
5	Sounder
6	Beacon
7	Fire Callpoint
8	Status Indicator LED
9	Visual Indicator
10	Sounder Visual Indicator Combined
11	Medical Callpoint
12	Evac Callpoint
13	Output Routing
14	Input 1
15	Input 2
	…
44	Input 31
45	Input 32
46	Output 1

47	Output 2
	...
60	Output 15
61	Output 16
62	Heat A1R

Number of bits used: 6

Serial Number

This parameter value carries the Serial Number read from the RBU or a specific plug-in.

Number of bits used: 32

Set / Reset

Used to set or reset an attribute or fault state. Set = 1; reset = 0.

Number of bits used: 1

Smoke Sensor Value

The analogue value read from a smoke sensor.

Number of bits used: 7

Sounder Fault

Fault codes for Sounder devices. Included in the Fault Signal message.

Number of bits used: 4

Value	Description
0	No Error
1	Type/Class Mismatch
2	Device ID/Serial Mismatch
3	Sounder Faulty (Sound fault detected)
4-15	Spare

Table 33: Sounder Fault Values

Spreading Factor

The spreading factor used for LoRa transceiver. This is limited to the range 6..12.

Number of bits used: 4

State

This parameter signals from the NCU to the RBUs which mode and state the mesh should be in. It is used by RUs to change which Mode and Stage they are in so that it can behave accordingly. The meanings of each value of this are listed below.

Number of bits used: 4

- 0000 Configuration Mode - Synchronisation Stage
- 0001 Configuration Mode - Mesh Formation Stage
- 0010 Active Mode
- 0011 Test Mode
- 0100 to 1111 RESERVED

Status Event

Part of the Status Indication message, this parameter identifies the event that generated the message to be generated.

Number of bits used: 8

Event Value	Event Description
0	None (status requested by NCU)
1	Child Node Added
2	Child Node Dropped
3	Primary Parent Added
4	Primary Parent Dropped
5	Secondary Parent Added
6	Secondary Parent Dropped
7	Primary Tracking Node Added
8	Primary Tracking Node Dropped
9	Secondary Tracking Node Added
10	Secondary Tracking Node Dropped
11	Secondary Parent Promoted to Primary Parent
12	Primary Tracking Node Promoted to Secondary Parent
13 - 255	Reserved

Table 34: List of Status Events

Status Event Node

Part of the Status Indication message, this parameter identifies the node that is associated with the Status Event field e.g. if the Status Event is “Child Node Added,” this parameter contains the node ID of the added child.

Number of bits used: 12

Status Flags

This parameter contains a bit map of all the possible faults and status flags for the RBU. A bit value of 0 indicates no fault present, a value of 1 indicates an active fault.

Number of bits used: 12

Status Flags Bit Index	Status Flag Description
0	Installation Tamper Fault (case / base removed from wall/ceiling)
1	Dismantle Tamper Fault (case opened / head removed from base)
2	Low Battery
3	Detector Fault
4	Beacon Fault
5	Sounder Fault
6	IO Input 1 Fault
7	IO Input 2 Fault
8 – 11	Reserved

Table 35: List of Status Flags

SVI

This parameter provides read and write (where permitted) access to the registers on the Sound and Visual Indicator board. The target register is addressed using the SVI Register value in field P1 of the command.

Number of bits used: 8

SVI Register

Contained in the P1 field of the SVI command, this parameter provides the SVI register address for the read or write operation.

Number of bits used: 8

Test Mode

Engineering test modes for development, testing, certification and commissioning. Test modes for each plug-in type to be added to the list of values.

Number of bits used: 8

Value	Description
0	Off
1	Receive
2	Transparent
3	Transmit
4	Monitoring
5	Sleep
6	Network monitor
3 - 255	Not used

Table 36: Test Mode Parameter Values

Tone Selection

This parameter value carries the tone selection control for sounder. The range of supported values is shown in Table 37.

Number of bits used: 6

Value	Tone Type	Tone Description	Req's
1		554Hz, 0.1s / 440Hz, 0.4s (AFNOR NF S 32 001)	SN5.12
2		500 – 1200Hz, 3.5s / 0.5s OFF (NEN 2575:2000)	SN5.12
3		420Hz 0.625s ON / 0.625s OFF (Australia AS1670 Alert tone)	SN5.12
4		500 – 1200Hz, 0.5s / 0.5s OFF x 3 / 1.5s OFF (AS1670 Evacuation)	SN5.12
5		970Hz, 0.5s ON / 0.5s OFF x 3 / 1.5s OFF (ISO 8201)	SN5.12
6		2850Hz (2900), 0.5s ON / 0.5s OFF x 3 / 1.5s OFF (ISO 8201 (US temporal HF))	SN5.12
7		1200Hz – 500Hz @ 1Hz (DIN 33 404)	SN5.12
8		500Hz – 1200Hz, 3.75s / 0.25s OFF (AS2220)	SN5.12
9		800 Hz continuous (LF contniuous tone BS5839)	SN5.12
10		970 Hz 0.5s ON/0.5s OFF (ISO 8201 LF BS5839 Pt1 1988)	SN5.12
11		2850Hz 0.5s ON/OFF (ISO 8201 HF)	SN5.12
12		660Hz 0.15s ON / 0.15s OFF (Swedish fire signal)	SN5.12

13		660Hz (Swedish All clear signal)	SN5.12
14		800Hz/970Hz @ 2Hz (FP 1063.1 Telecom)	SN5.12
15		1000 – 2500Hz, 0.5s / 0.5s OFF x 3 / 1.5s OFF (AS1670 Evacuation)	SN5.12
16		950Hz 0.5s ON/ 0.5s OFF x 3 / 1.5s OFF repeat (US temporal LF)	SN5.12
17		970Hz continuous	SN5.12
18		800Hz – 970Hz @ 3Hz	SN5.12
19		800Hz – 970Hz @ 9Hz	SN5.12
20		2400Hz continuous	SN5.12
21		970Hz, 0.5s / 630Hz, 0.5s	SN5.12
22		800Hz – 970Hz @1Hz	SN5.12
23		800Hz – 970Hz @ 100Hz	SN5.12
24		2400Hz – 2900Hz @ 9Hz	SN5.12
25		2400Hz – 2900Hz @ 3Hz	SN5.12
26		Dual tone 800/630 Hz @2Hz - **Default Fire Tone**	SN5.12
27		400Hz continuous	SN5.12
28		550Hz / 440Hz @ 0.5Hz	SN5.12
29		1500Hz – 2700Hz @ 3Hz	SN5.12
30		550Hz, 0.7s / 1000Hz, 0.33s	SN5.12
31		250Hz – 1200Hz @ 12Hz	SN5.12
32		800 / 1000Hz 0.5s each (1Hz)	SN5.12
33		Dual tone 800/630 Hz @2Hz - 1s ON / 8s OFF - **Default First Aid tone**	
34		Silent tone	
35		Test tone 800Hz 0.1s ON / 2s OFF	
36 – 63		Reserved	

Table 37: Tone Selection Parameter Values

Transaction ID

This is used to identify a COMMAND-RESPONSE transaction. Both messages use the same transaction ID. The Transaction ID is incremented for each new transaction

Number of bits used: 3

Tx Power

The maximum transmit power used by the LoRa transceiver

Number of bits used: 2

Value	Description
0	7 dBm
1	13 dBm
2	17 dBm
3	20 dBm

Table 38: Tx Power Parameter Values

Unit Address

The unit address of the device that is being instructed to shut down. The unit address is numerically equal to 32 * Zone No. + Unit No. within Zone.

Number of bits used: 9

Programmed Zone

A command to remotely read or write the programmed zone number of an RBU.

Number of bits used: 12

Zone

When used in the P2 field of a command, this provides zonal addressing for the command.

To address the command to all nodes in a zone, the destination address is set to GLOBAL (0xFFF) and the target zone is entered in this field. If this value is also set to GLOBAL (0xFF) the command is applied to all nodes in the network. If the destination address of the command is set for a specific node, this parameter is ignored.

Number of bits used: 8

8.3 Message Sequence Charts

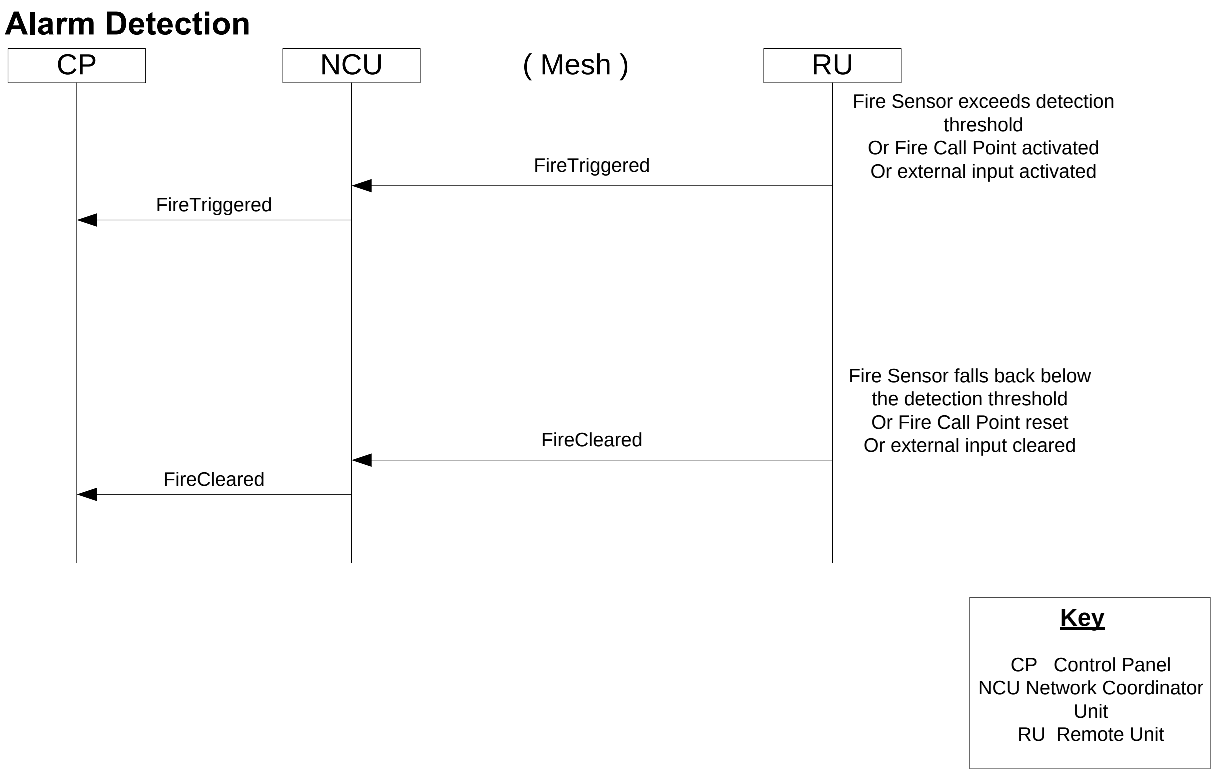


Figure 37: Fire Alarm Detected MSC

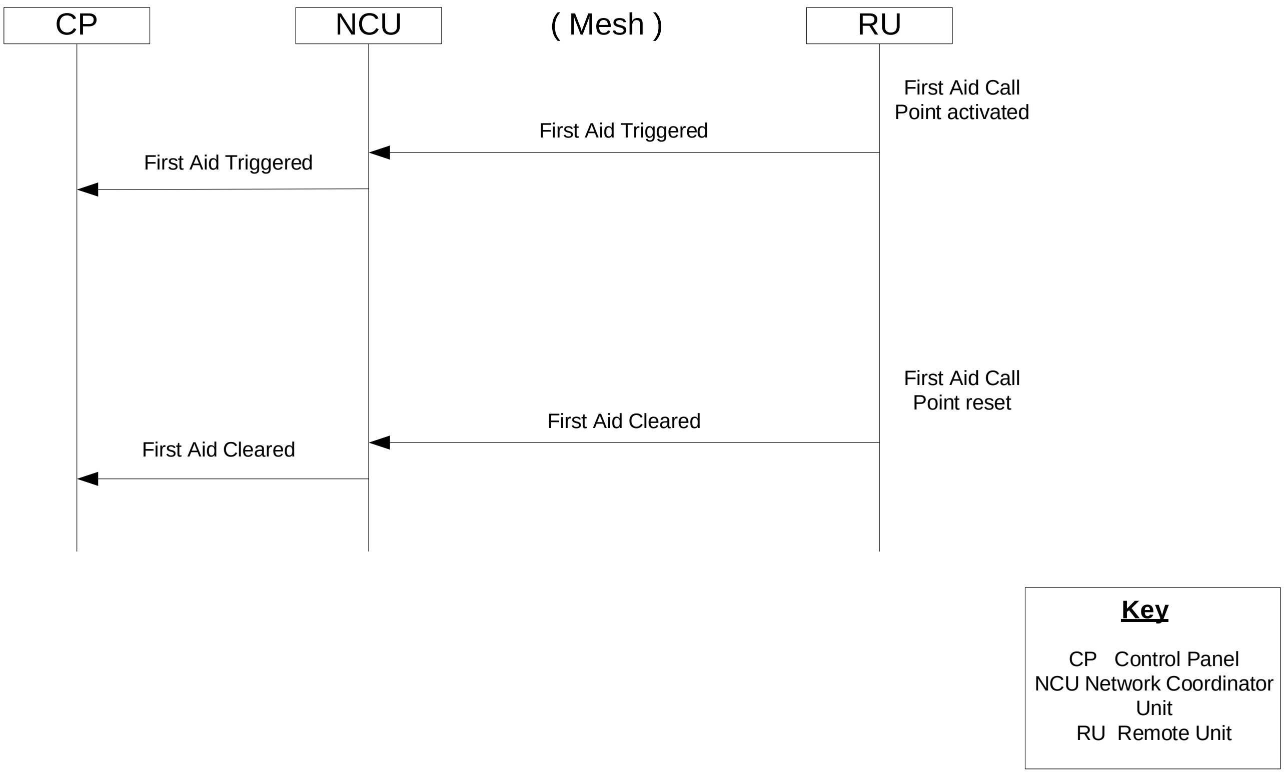


Figure 38: First Aid Alarm Detected MSC

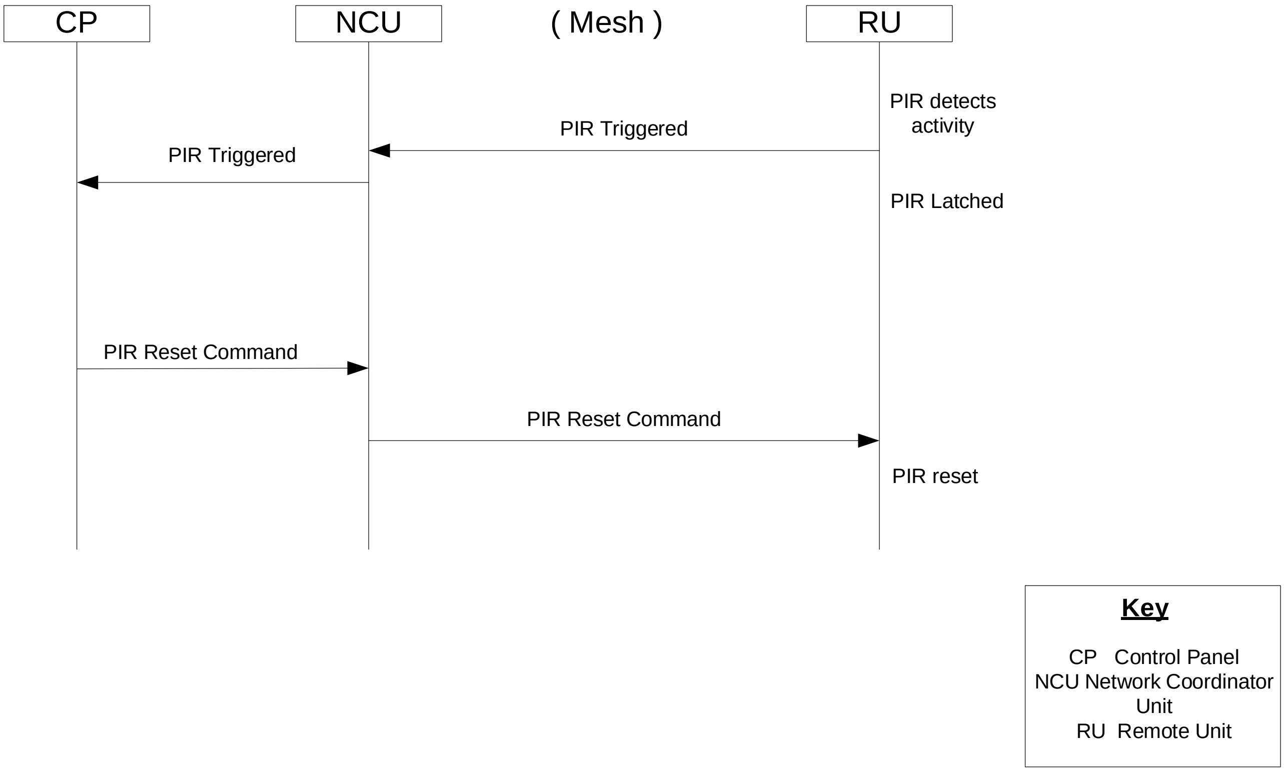


Figure 39: PIR Alarm Detected MSC

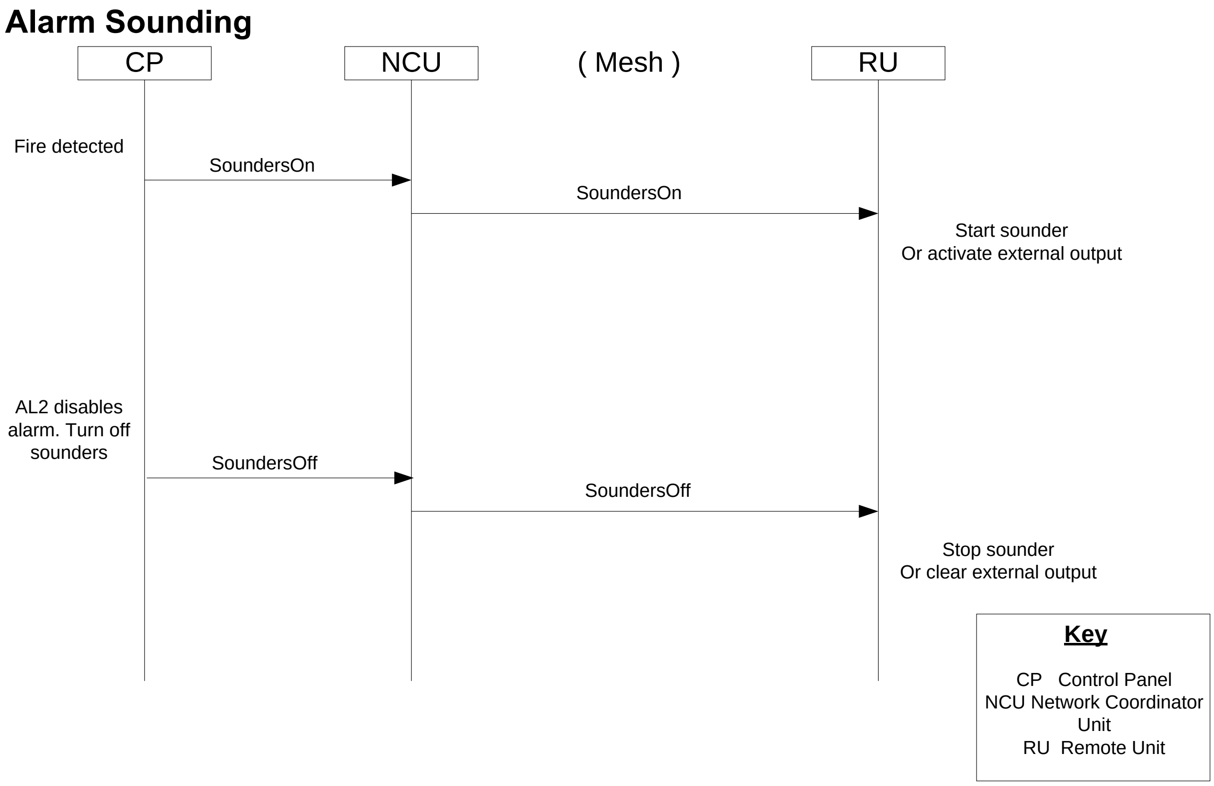


Figure 40: Alarm Sounding MSC

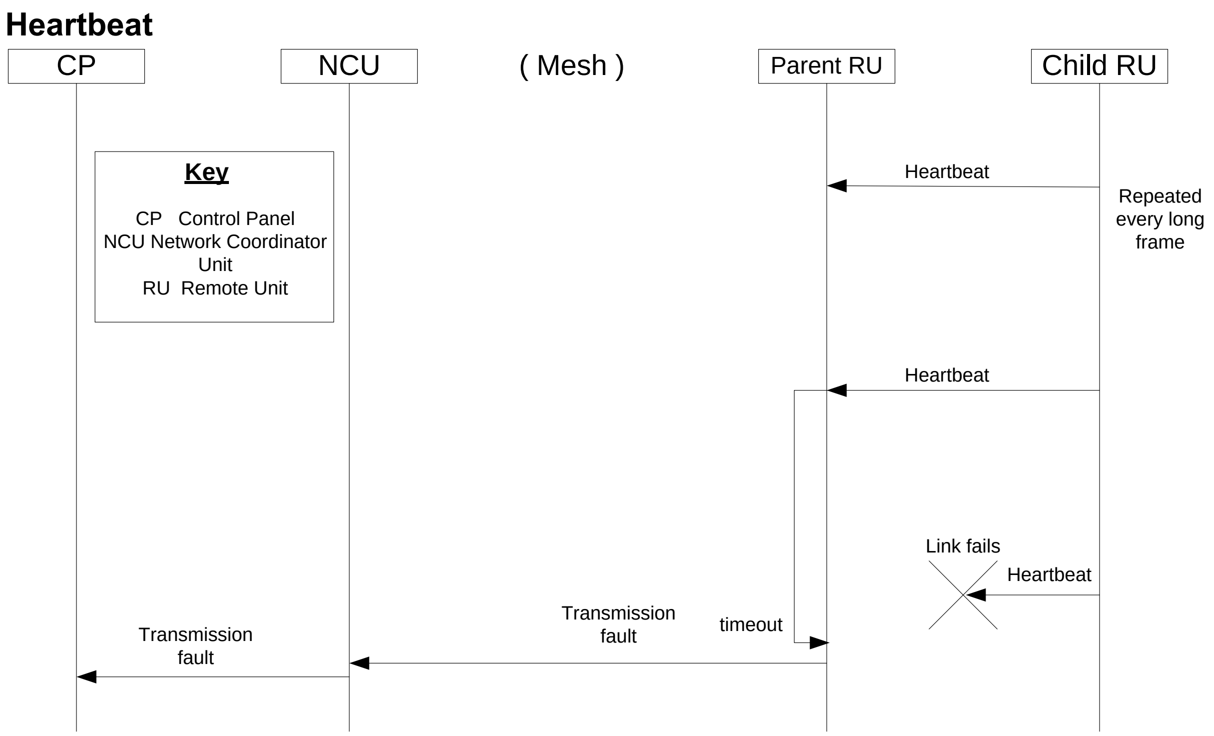


Figure 41: Heartbeat MSC

Parameter Write

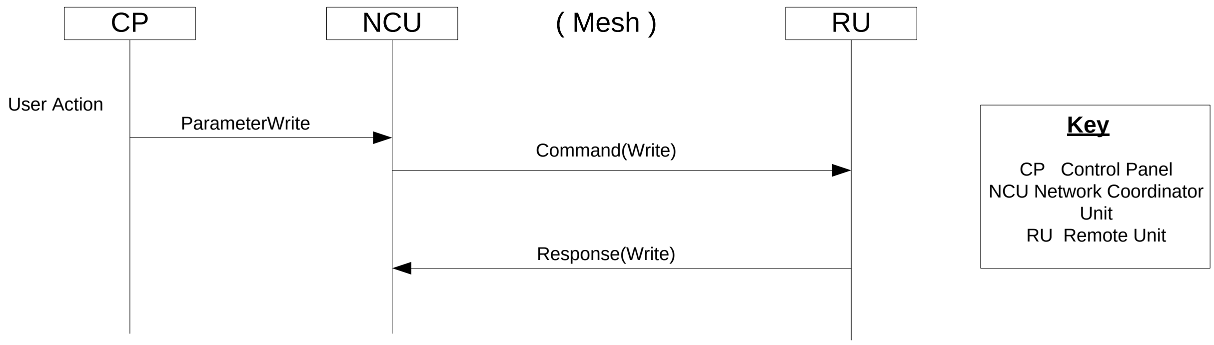


Figure 42: Parameter Write from Control Panel

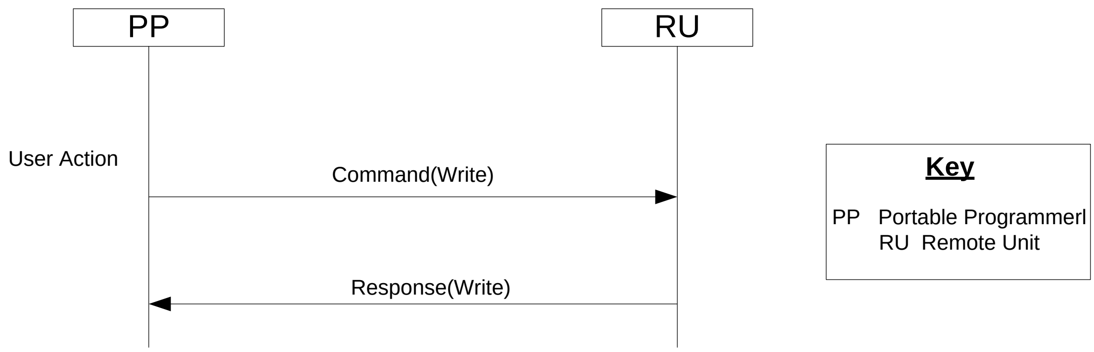


Figure 43: Parameter Write from Portable Programmer

Parameter Read

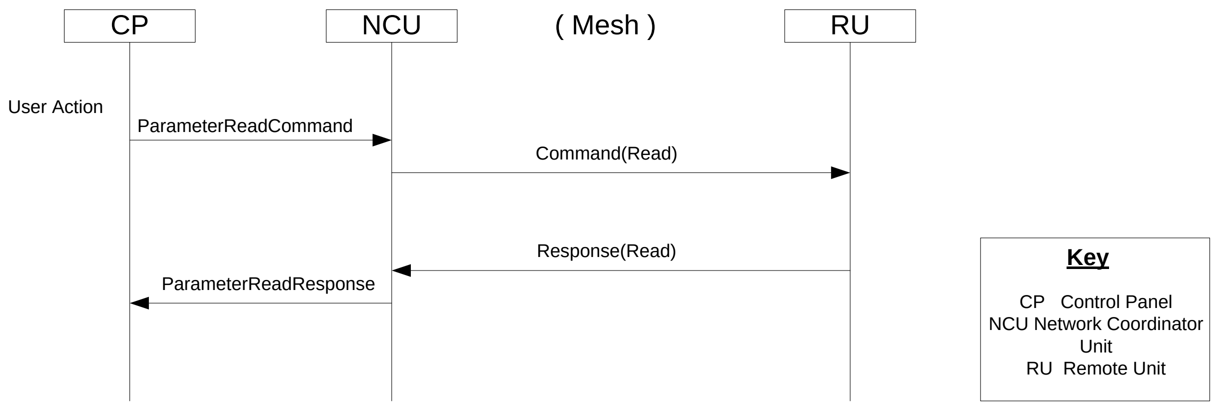


Figure 44: Parameter Read to Control Panel

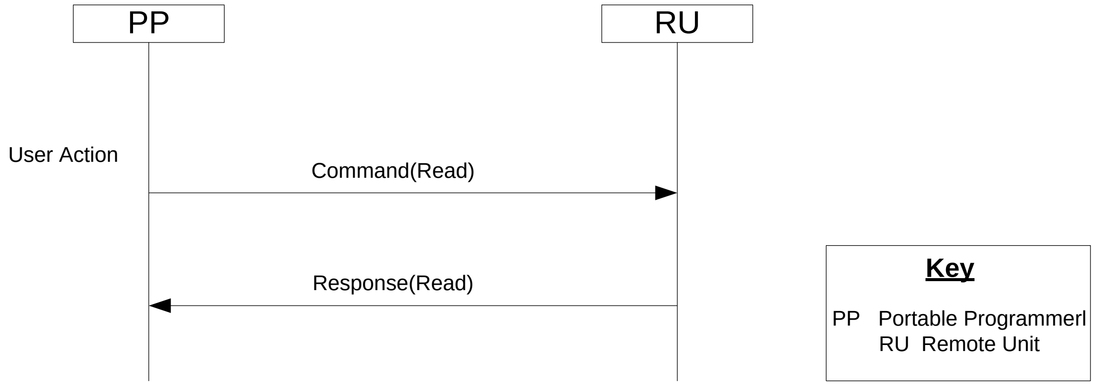


Figure 45: Parameter Read to Portable Programmer

Firmware update - wireless

8.4 Configurable Parameters

Parameter	Description
CMD_RSP_TIMER	Duration of Command-Response transaction timer

Table 39: Application Configurable Parameters

9 PORTABLE PROGRAMMER

The portable programmer is limited to a single point-to-point connection with a device at any one time. It can interact with equipment using the connection types shown in Table 40.

Connection Type	Connection Medium	Synchronisation Master
Wired	RS232	N/A
Standalone Wireless	Wireless mesh protocol	PP
Networked Wireless	Wireless mesh protocol	NCU

Table 40: Portable Programmer Connection Types

These connection types are described further in the sections below.

9.1 Wired Connection

The Portable Programmer can connect to an RU using a wired connection. This is an RS232 interface that supports the AT format commands described in Appendix F.

The messages sent over this interface are not encrypted.

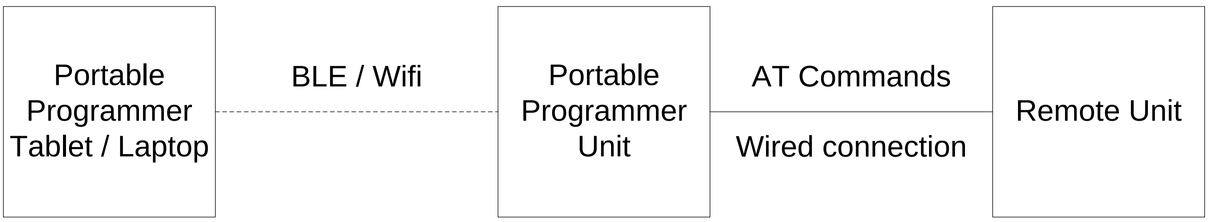


Figure 46: Portable Programmer Wired Connection

9.2 Standalone Wireless Connection

The Portable Programmer is able to connect to an RU using a standalone wireless connection. This mode does not require an NCU or existing mesh to be in place. The Portable Programmer acts as the master for the TDM structure and the RU synchronises to the Portable Programmer.

Slots in the following channels of the TDM structure are used to send messages in both directions between the PP and the RU:

- Messages from the PP to the RU use the DL CCH channel
- Messages from the RU to the PP use the RACH 2 channel

Once the PP and RU are synchronised, the Portable Programmer can set the address of the RU. This involves the 'SetAddress' MAC layer frame type which addresses the RU by its serial number.

After the RU address has been set, the Portable Programmer can communicate with the Remote unit using the Command and Response messages which address the RU by the address.

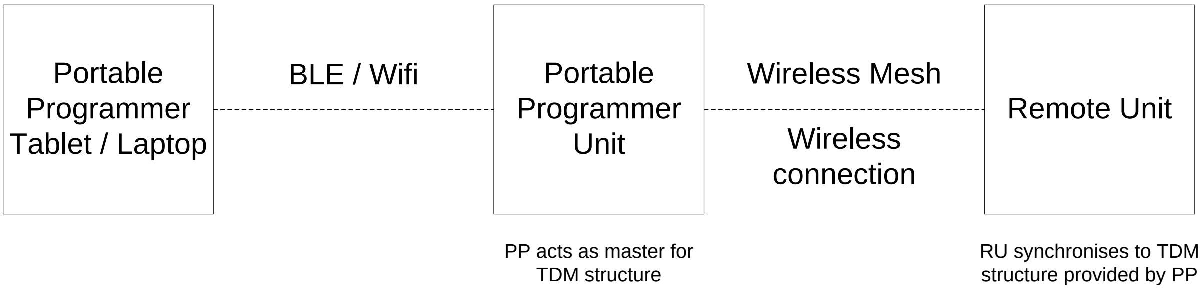


Figure 47: Portable Programmer Standalone Wireless Connection

9.3 Networked Wireless Connection

The Portable Programmer is able to connect to an RU using a Networked wireless connection. This mode requires an existing mesh to be in place. Both the Portable Programmer and the RU synchronise to the TDM structure provided by the mesh.

Slots in the following channels of the TDM structure are used to send messages in both directions between the PP and the RU:

- Messages from the PP to the RU use the DL CCH channel
- Messages from the RU to the PP use the RACH 2 channel

The address of the RU needs to be set before it joins the mesh.

Once the PP and RU are synchronised to the mesh, the Portable Programmer can communicate with the Remote unit using the Command and Response messages which address the RU by the address.

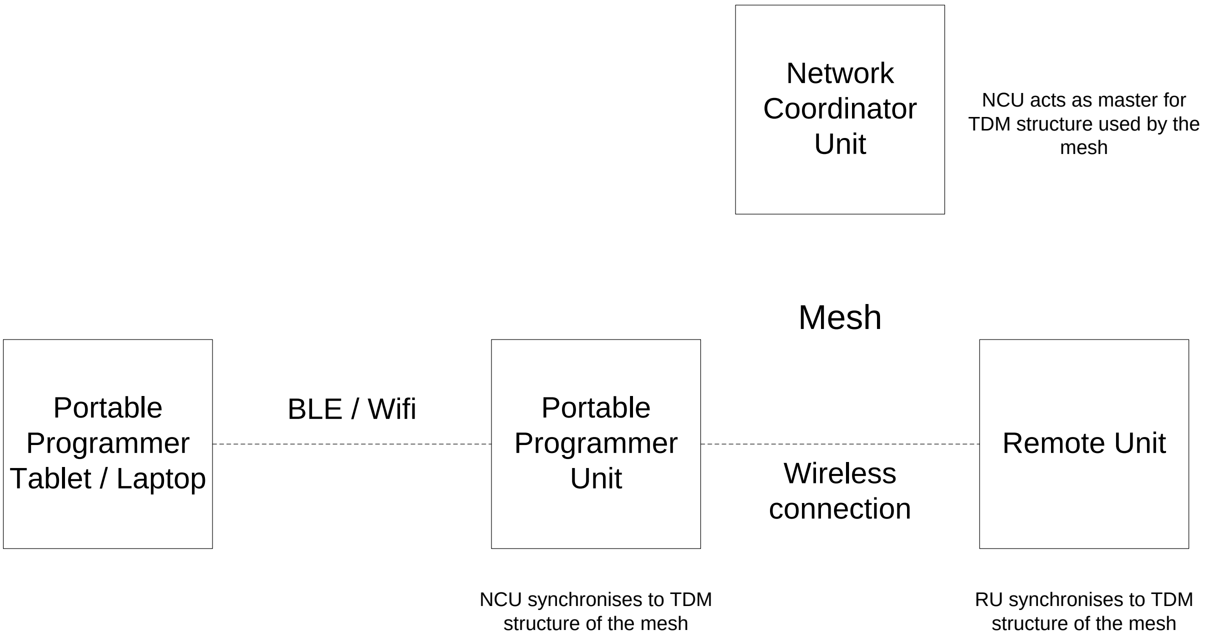


Figure 48: Portable Programmer Network Wired Connection

If the Portable Programmer connects to the NCU it is able to access RUs remotely over the mesh.

10 FIRMWARE UPDATE

The software on the RU is structured so that it has a bootloader image which runs initially which then loads the application image. These are described further below:

Bootloader Image

The bootloader is a simple software image. When the unit is powered up in normal operation the bootloader selects the active application image which is stored in flash memory and runs it.

The bootloader also includes mechanisms for storing new application images in the flash. It supports the following firmware update mechanisms:

- Wired Update
- Wireless Update to a single unit

The bootloader is loaded into flash in the factory and cannot be overwritten after leaving the factory. This approach ensures that a user is able to load new application software even when the unit contains corrupt application images that do not run.

Application Image

The application contains the bulk of software for the unit. This includes the mesh protocol and the application software.

The flash memory is partitioned to store two application images. This allows the unit to run the code in one partition and update the image in the other partition. This is required for the 'Wireless firmware update to full system' mechanism which uses the Wireless Mesh protocol to transfer the image being downloaded. This approach is described further below.

When the RU is powered up the bootloader selects the active application image and runs it.

The application image only contains a single firmware update mechanism:

- Wireless Update to the full system

The application images are loaded into flash in the factory. However these can also be overwritten after leaving the factory using one of the firmware update mechanisms.

Version Control

The RU uses the data model in Figure 49 to track the application images stored in flash memory.

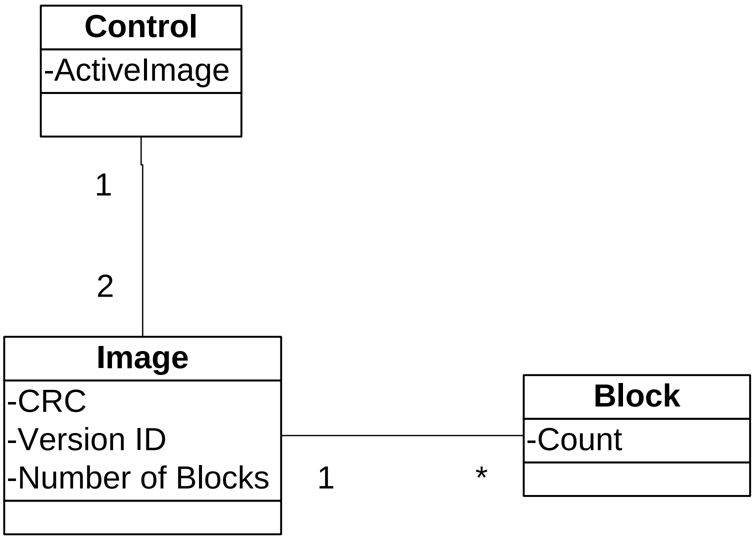


Figure 49: Firmware Control Data Model

10.1 Wired Firmware Update

This type of firmware update uses the wired connection to the remote unit. This is the same wired connection for a portable programmer that is described in section 9.1.

The AT commands in Table 41 are available to control a wired firmware update.

AT Command	Description
ATFI	Gets firmware information
ATR	Reboots unit
ATBOOT	Enter the bootloader mode
ATBPPU	Select the PPU UART port to be used by the bootloader

Table 41: AT commands for wired firmware update

The image is transferred in a raw binary format using the YMODEM Protocol and overwrite the existing Software application.

The image should be first decrypted if encryption is used for the Wired Firmware Update. The encryption should use the session key for the network.

After image transfer, the bootloader verifies the integrity of the application by checking the image CRC and the top of the stack address in the vector table. If the application is valid then the Bootloader will jump to the new application and it starts executing.

The Flowchart below summarises the Boot and Firmware-Update functionalities implemented in the Bootloader:

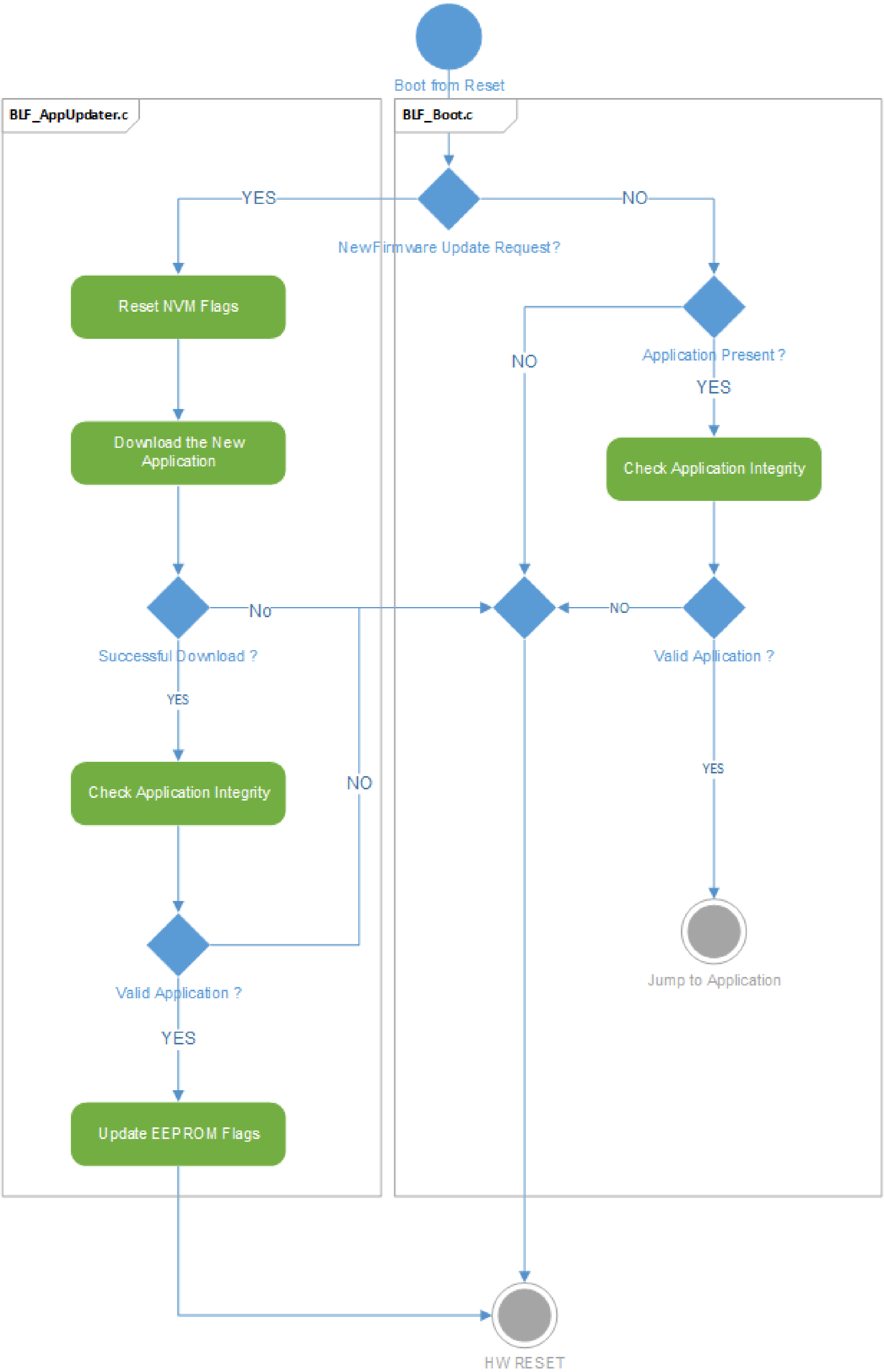

Boot from Reset
BLF_AppUpdater.c
BLF_Boot.c
YES
NO
NewFirmware Update Request?
Reset NVM Flags
Application Present ?
NO
YES
Download the New Application
Check Application Integrity
No
NO
Successful Download ?
Valid Application ?
YES
YES
Check Application Integrity
NO
Jump to Application
Valid Application ?
YES
Update EEPROM Flags
HW RESET

Figure 50: Bootloader Flowchart

The user can read the firmware information and the CRC value using the AFTI command to verify that the firmware is successfully updated.

Assuming an image size of 81kBytes and a transfer rate of 10 packets of 100 bytes every second then the estimated time to download an image using this mechanism will be 81 seconds.

10.2 Wireless Firmware Update to Single Unit

This type of firmware update uses a wireless connection to the remote unit. The control messages use the same wireless connection for a portable programmer that is described in section 9.2

The Application commands in Table 42 are available to control a wireless firmware update to a single unit.

Application Command	Description
Read (Firmware Information)	Gets firmware information
Read / Write (Firmware Active Image)	Gets / Sets active image in firmware control
Write (Reboot)	Reboots unit

Table 42: Application commands for wireless firmware update to single unit

The image is transferred using a dedicated image transfer protocol which is shown in Figure 51. It was not possible to use the wireless mesh protocol because this is not designed for transferring images and would be very slow. A new protocol has been created with data packets of 255 (the max permitted by the LoRa chips) to increase the transfer rate. Data transfer rates of approximately 2kBytes/sec are predicted for a 250kHz modulation bandwidth channel.

Packets are fixed size and have the following fields:

Field	Size in PP to RU packets	Size in RU to PP packets
Frame type	4	4
Serial number of RU	32	32
Length byte	8	8
Data	1992	32

Table 43: packet format for wireless firmware update to a single unit

The LoRa CRC is used to check for transmission errors in both directions.

The image transferred will be encrypted using the session key for the network (not implemented).

After image transfer the user can read the firmware information to check that the CRC is correct for the image and make the new image the active image. The user can then reboot the unit and the new image will be executed.

An image size of 81kBytes can be segmented into 325 packets of 249 bytes. Assuming the transaction to transfer each packet takes 0.5 seconds then the estimated download time is 325 x 0.5 = 162 seconds.

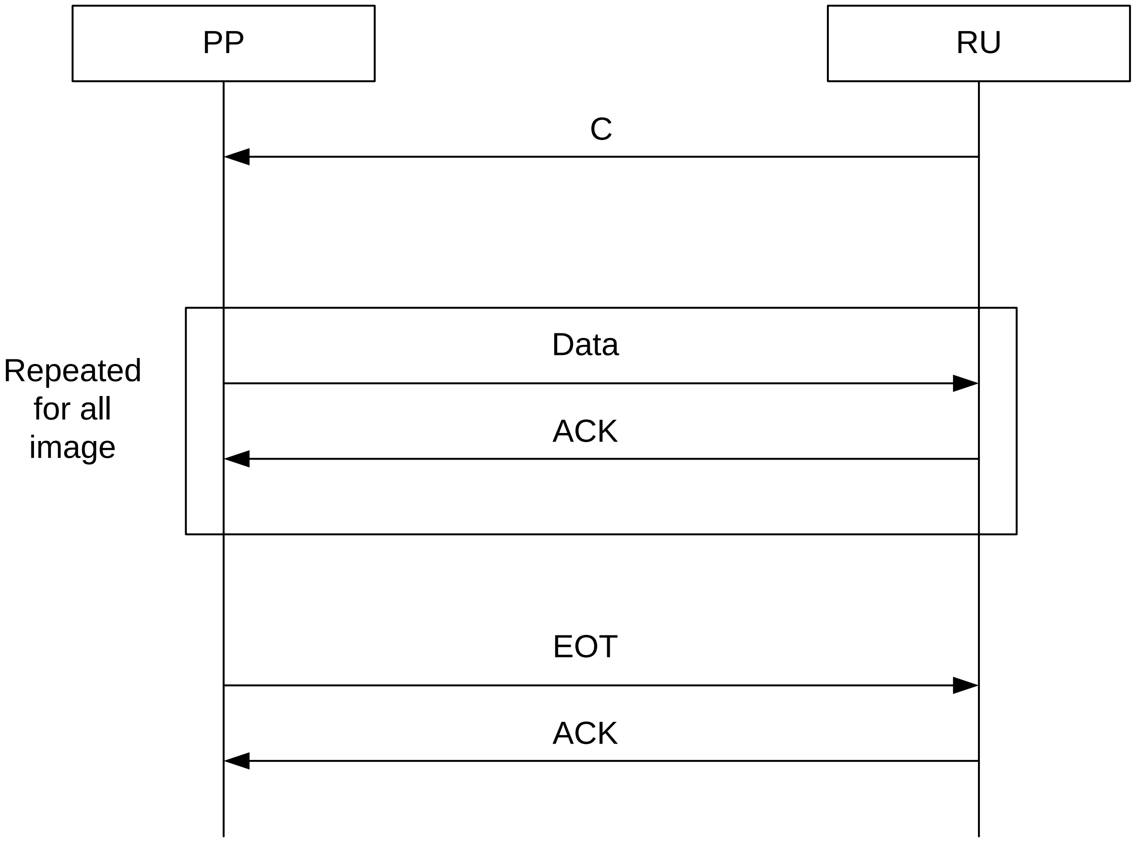


Figure 51: Wireless Firmware Update to single unit MSC

10.3 Wireless Firmware Update to Full System

This type of firmware update involves transferring an image from the NCU to all RUs in the network. This is designed to happen in the background of a wireless mesh system that is operational.

The new firmware image is first loaded onto the NCU. The mechanism to load the image onto the NCU is outside the scope of this document.

The Application commands in Table 44 are available to control a wireless firmware update to a full system.

Application Command	Description
Read (Firmware Information)	Gets firmware information
Write (Firmware Download Start)	Prepares the RUs to receive the firmware image

Firmware	Downloads a Firmware block
Read / Write (Firmware Active Image)	Gets / Sets active image in firmware control
Write (Reboot)	Reboots unit

Table 44: Application commands for wireless firmware update to full system

The NCU first send the Firmware Download Start which contains the size of the image to be transferred. It then sends through the firmware image a block at a time. These are broadcast to all the RUs. The blocks are encrypted using the session key for the network. Each RU stores the blocks as they are received.

Periodically (once per hour during firmware upgrade) each RU sends a status indication message to the NCU. This contains the following information about the firmware transfer:

- Number of blocks still outstanding
- Count of first outstanding block
- CRC of image

When the NCU has transferred the complete firmware image it waits until it receives Status Indications from the RU. If any RUs report that they still have outstanding blocks then the NCU sends these blocks. When all the RUs report that they have received all the blocks and CRCs are correct then the firmware transfer is complete.

After image transfer the user can read the firmware information to check that the CRC is correct for the image and make the new image the active image. The user can then reboot the unit and the new image will be executed.

The images are transferred 12 bytes at a time. If a block is sent every 2 seconds then an 81kbyte image will be transferred in 81000 * 2 / 12 seconds = 13500 secs = 3.7 hours.

The estimated transfer time will be 5 hours allowing for retransmissions.

A References

1. WirelessHART, BS EN 62591:2016
2. IEEE Std 802.15.4.2020, IEEE Standard for Low-Rate Wireless Networks
3. Cygnus Group Development Project Proposal v1.0, 15 November 2016, P028575
4. HFY-16-0011-D_A4 Cygnus 2 Mesh Protocol Proposal
5. HFY-16-0007-D_A8 Phase 1b Report
6. HKD-16-0003-D_A3 Cygnus 2 System Architecture - Diagrams
7. 2000-SPC-0006-02B System Requirements Specification (formerly HFY-16-0005-D_H5 System Requirements Specification)
8. HFY-16-0017-D Devolved Radio Requirements
9. LoRaWAN
10. HKD-17-0038-D_A Compliance of Mesh Protocol Design against Devolved Radio Requirements
11. HKD-17-0017-D_A3 Link Check Options
12. RFC6550 – RPL: IPv6 Routing Protocol for Low Power and Lossy Networks
13. 1000-DBA-0001-05 Mesh Forming Scenarios
14. 1000-DBA-0002-01 Mesh Healing Scenarios
15. Semtech Application Note, ETSI Compliance of the SX1272/3 LoRa Modem
16. SX1272/73 datasheet (Rev . 4 - January 2019)
17. Semtech LoRa FAQ document
18. ETSI EN 300 220-1 V3.1.1
19. ETSI EN 300 220-1 V2.4.1
20. ETSI EN 300 220-2 V3.2.1
21. HKD-17-0044-OP Mesh Traffic Analysis (absent from server)
22. HKD-17-0047-D Power Calculation Spreadsheet
23. HKD-17-0053-OP Compendium of Advanced Mesh Techniques
24. HKD-17-0057-D Channel Hopping Algorithm
25. HKD-17-0065-D Mesh Protocol Message Lengths
26. HKD-17-0053-OP Simulation Results
27. HKD-17-0045-OP Cygnus 2 Encryption
28. 2000-SPC-0007-02A Mesh Forming and Healing (formerly HKD-17-0329-D Forming and Healing)
29. 2000-SPC-0009-01 Software Architecture and Design Specification (formerly HKD-17-0076-D Software Architecture and Design Document)

B Requirements Traceability

The mapping between the requirements in the System Requirements Document and this document is contained in HKD-17-0038-D Compliance of Mesh Protocol Design against Devolved Radio Requirements [10].

C Information Flows

Requirements from System Requirements Specification [7] and Devolved Radio Requirements [**Error! Reference source not found.**]

Information Flow	Source	Destination	ON DEMAND / REPEATED	Requirement	Priority
Alarm detection	RU	NCU	ON DEMAND	RB7.5	Mandatory
Alarm sounding	NCU	RU	ON DEMAND		
Heartbeat	RU	NCU	REPEATED	RB5.9	Mandatory
Synchronisation	NCU	RU	REPEATED		
Parameter write	NCU / PP	RU	ON DEMAND	C1.12,NC1.3, RB5.8,S1.2	1,2,3
Parameter read	RU	NCU / PP	ON DEMAND	C1.8,C1.9	1
Firmware update - wireless	PP	RU / NCU	ON DEMAND	S1.5	1

Table 45: Information Flows

D Glossary

Term	Description
ACK	Acknowledgement
AT	Hayes command set (AT stands for Attention)
BW	Bandwidth
CAD	Channel Activity Detect (for LoRa)
CP	Control Panel
CRC	Cyclic Redundancy Check
DCH	Dedicated Channel
DL-CCH	Downlink Common Channel
LoRa	Long Range, low power modulation technique from Semtech
MAC	Medium Access Control layer of protocol stack
MCU	Microcontroller Unit
MSC	Message Sequence Chart
NCU	Network Coordinator Unit
NPDU	Network Layer Protocol Data Unit
P1	Parameter 1 (context specific)
P2	Parameter 2 (context specific)
PHY	Physical layer of protocol stack
PIR	Passive Infra-Red
PP	Portable Programmer
RACH	Random Access Channel
RBU	Radio Base Unit
RRC	Radio Resource Controller
RTC	Real Time Clock
RU	Radio Unit
SRD	System Requirements Document
TDM	Time Division Multiplexed

Table 46: Memory Estimate

E Message Transfer Rates

This section contains estimates of the message transfer rates for the information flows in the mesh network. The figures are due an update. The section uses the Information Flows that were identified in Appendix C.

These estimates were used to select the slot duration and the numbers of slots allocated to each channel in the TDM structure (described in 6.1). The estimates have concentrated on the information flows that have timing requirements in EN54. There is no requirement for the information transfer rates for Parameter read / write and firmware update, so assumptions have been made for those rates.

Later in the development process, channel sizes were changed based on simulation results.

The message transfer rate estimates use the following assumptions:

- Maximum size mesh of 512 nodes (including the NCU)
- Mesh depth of 8
- Timings for alarm detection and output transmission as shown in Figure 52
- Parameter read / write and firmware update with message transfer rate of 4 messages per second for S-RACH and 4 messages per second for DL-CCH

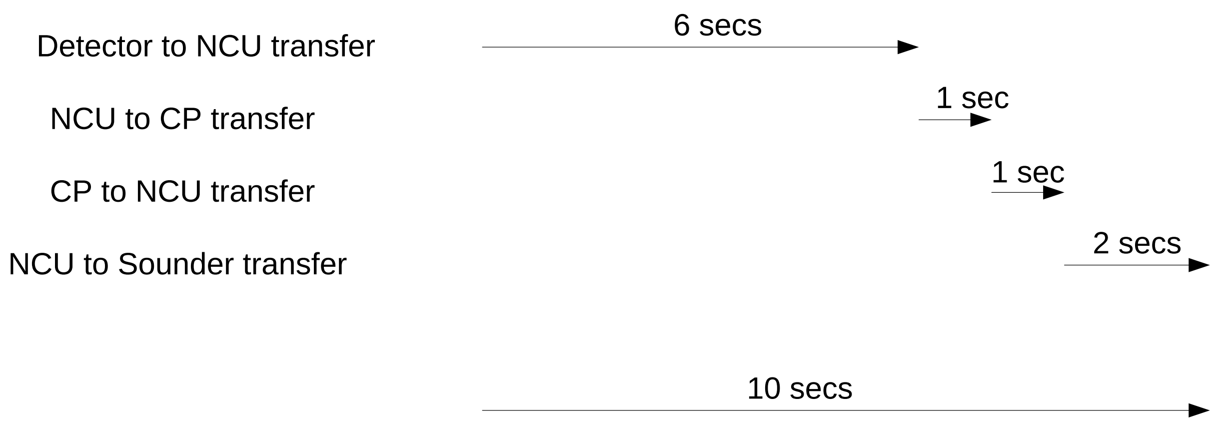


Figure 52: Detection and Sounding Timing Assumption Diagram

Fire Alarm Detection

Description	Value	Note
Max transfer time requirement (secs)	6	7 - 1 for CP link
Max number of hops across mesh assumption	8	
Common channel multiplier to allow for retransmissions	4	
Message transfer rate (msgs per sec)	5.3	

First Aid and PIR Alarm Detection

Description	Value	Note
Max transfer time requirement (secs)	6	Assume same as fire
Max number of hops across mesh assumption	8	
Common channel multiplier to allow for retransmissions	4	
Message transfer rate (msgs per sec)	5.3	

Alarm Sounding

Description	Value	Note
Max transfer time requirement (secs)	2	3 - 1 for CP link
Max number of hops across mesh assumption	8	
Message transfer rate (msgs per sec)	4	

Heartbeat + Synchronisation

Description	Value	Note
Number of RU's	512	
Heartbeat transmit period in secs	193.75	
Message transfer rate (msgs per sec)	6	

Parameter Write + Read + Firmware update – wireless

Description	Value	Note
S-RACH message transfer rate (msgs per sec)	4	Assumed rate
DL-CCH message transfer rate (msgs per sec)	4	Assumed rate

Breakdown by Channel

Description	P-RACH	S-RACH	DL-CCH	DCH
Alarm Detection (fire)	5.3			
Alarm Detection (first aid and PIR)		5.3		
Alarm Sounding			4	
Heartbeat + Synchronisation				6
Parameter Write + Parameter Read + Firmware Update - wireless		4	4	

Total

Description	Value	Note
Total (msgs per sec)	28.6	Sum of breakdown table

F AT Commands

AT commands are described in the 2000-SPC-0009-01 Software Architecture and Design Specification [29].

G Energy Consumption and Battery Life Estimates

Energy consumption and battery life estimates are maintained in the HKD-17-0047-D Power Calculation Spreadsheet [22].