CYGNUS SMARTNET

MESH FORMING AND HEALING SPECIFICATION

2001-SPC-0007 REV 02

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Document revision history

Rev	Description	Date Approved	Author	Checked	Approved
A1	Initial Version	15 Dec 17	AT		
A2	Stage Change message renamed as SetState message	18 Dec 17	AT		
A2	Some corrections to use of the SACH channel, and Section 5.1.1 added to describe which SAS type they use.	08 Jan 18	AT		
A3	Updates to duration and precise details of the synchronisation stage. Term StageChange corrected to SetState. Section 5.1.1 added, describing the mapping of the SACH messages onto the SACH channels.	15 Jan 18	AT		
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B1	Changes after review of mesh forming sections by Cygnus Group. (No review yet of mesh healing sections.)	02 Feb 18	AT		
B	Formally issued. No changes since B1.	02 Feb 18	AT		
C1	Added description of procedure for Parent Selection Process and Parent Replacement Process.	06 Feb 18	AT		
C2	Incorporated changes following review by Cygnus Group of Mesh Healing (Section 4).	12 Feb 18	AT		
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D1	Modified description of rank selection in Section 3.1.3 to show that on first sweep devices are seeking two parents, but on second sweep they will accept one parent. Modified the description of criteria for performing Node Loss and Associated Node Loss processes in section 4.2.	18 Feb 18	AT		
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E1	Changes after further review by Bull, received by e-mail 20th Feb.	21 Feb 18	AT		
E	Formally issued after review by Peter Whitworth. No changes since E1.	21 Feb 18	AT		
F1	Refinements to description of Associated Node Loss Process and Parent Refresh Process. Status message at completion of the Associated Node Loss Process sent in Child-SAS rather than Mesh-SAS. Description added for Timeout of mesh formation stage. Description of rank selection process modified to show extension of period spent evaluating each rank from one to multiple long frames. Appendix A added: Mesh Forming/Healing Constants	06 Mar 18	AT		
F2	Table 2 added, describing the low-duty-cycle, low-power mode. Description of behaviour on "Loss of All Parent and Tracking Nodes" added to Section 4.2.2 "Associated Node Loss Process". Added Section 7.2 "Handling Asymmetric Decisions within the Mesh".				
F3	Changes made in response to review comments by Peter W.				
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F5	Updated the Mesh Formation description to include a minimum RSSI requirement when selecting candidate parents	09 Aug 18	PC		
G	Included timeouts for Synchronization and Mesh Formation stages	19 Sep 18	RM		
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01	Ported from ...F5 PA document to CGL template. Included time-outs for Synchronization and Mesh Formation Stages.	25 Sep 18	PA	RM, SG	RM, SG
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01	Ported to Cygnus template	25 Mar 20	AK	PC	GH
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02	Updated entire document for change to DULCH operation and replaced references to diagrams in HKD-17-329-D with the actual diagrams	19 Aug 21	Peter Connolly PC Digitally signed by Peter Connolly Date: 2021.08.26 13:56:08 +01'00'	Alastair Knight Digitally signed by Alastair Knight Date: 2021.08.26 15:11:20 +01'00'	Giles Hemmings Digitally signed by Giles Hemmings Date: 2021.08.26 16:18:45 +01'00'

CONTENTS

GLOSSARY AND TERMS

Term	Definition
Parent Node	The term parent node describes any node's relationship to its child nodes. A parent is one of two nodes (Primary and Secondary Parent) that has the responsibility to another node (Child Node) to monitor its heartbeat and to report to the NCU if that child node cannot be detected and has hence left the mesh. They are also responsible for forwarding RACH messages that have been sent by the child node onto their own parents, and so forth until the RACH message arrives at the NCU. Forwarding of a RACH node alternates between the Primary and Secondary parent, starting in each case with the Primary Parent node. They also provide a timing reference to the child node, based on the arrival time at the child node of the Heartbeat message sent on the DCH. Selected by the child, subject to agreement by the parent.
Tracking Node	The tracking nodes (primary and secondary) are the quick-swap replacements in the event that a child node loses one of its parent nodes (e.g. due to insufficient signal reception). The Primary Tracking node is the more preferable of the two for this purpose, as established by the child node by comparing the Number of Children and received SNR of each tracking node. They also provide a timing reference to the child node, based on the arrival time at the child node of the Heartbeat message sent on the DCH. Selected by the child, without need for agreement by the tracking node. (Agreement is sought only if the tracking node is promoted to a parent node).
Child Node	The term child-node describes any node's relationship to its parent nodes. A child node is responsible for forwarding a DLCCH message originated by the NCU. It is not always the case that the DLCCH will have been sent by the parent (a preferred parent is one having fewer children, not necessarily the one with the best SNR), but it will often be the case.
Candidate Parent	The term candidate parent describes the relationship of a node to a candidate child node when that candidate child node is currently requesting (or has identified it for possible future requests) to make the candidate parent node into a parent node.
Candidate Child	See candidate parent.
Mesh State: Off	The condition of the mesh when no heartbeats are being sent from any device, including the NCU.
Mesh State: On	The NCU is transmitting its heartbeat: some or all of the RBUs will also be transmitting heartbeats; all other devices are waiting to receive and synchronise to a heartbeat before transmitting their own.
RACH	Random Access Slot. An acknowledged physical channel that can be accessed for transmission at any time by any device.
DULCH	Delayed Uplink Channel. A virtual channel that sits on top of the RACH and differs only in that any one device has specific slots in which it can transfer a new message into the appropriate RACH queue. (Note that the DULCH is only used for the initial transmission of any message: re-transmissions (of each message including exponential-backoff by the same node and forwarding by subsequent nodes) are handled by the RACH, and are not subject to the slot restrictions of the DULCH).
SAS	DULCH Access Slot. This is the slot in which a particular RBU is allowed to transmit on the DULCH. Different slots are defined depending on whether the RBUs expected to transmit are Mesh-wide (Mesh-SAS), Zone-wide (Zone-SAS), or the children of a common parent (Child-SAS).

1 OVERVIEW

Mesh Forming covers those behaviours that occur after an installation engineer has installed the NCU and all the RBUs, and first instructs the NCU to transmit its heartbeat, and concludes after the RBUs are connected and active on the mesh network.

Mesh Healing covers those behaviours that occur if a device is re-started (either autonomously, or by the action of the engineer) after the mesh formation process has been started, and those behaviours that occur within the mesh that either result-in or by-design-lead-to a change of mesh configuration.

Sequential tasks are run to implement the mesh forming. These are: an initial Programming Stage to program an RBU with mesh and device specific information; a Synchronisation Stage in which an RBU acquires timing synchronisation with another device within the mesh; a Mesh Formation Stage in which the RBU selects either the NCU or a pair of equal-ranked nodes as parents, and other child nodes may select it as a parent; and then finally the Active Mode, which provides the normal de-facto behaviour.

Background tasks are run to manage the Load Balancing, Node Loss and Parent Refresh processes. The Load Balancing Process is started during the Mesh Configuration Stage, and the Node Loss Process is started during the Active Mode. The Parent Refresh Process is called on demand from the Node Loss Process. These processes are all run as background tasks, and can take many seconds or minutes to complete.

2 PHYSICAL LAYER CHANNELS

In order to support the mesh forming and healing, the mesh needs to support the following four types of communications with minimal latency and without compromising the EN54 fire and output signal performance.

Node to NCU	Node to NCU messages are sent across multiple mesh hops using acknowledged RACH messages, where the MAC Destination field is set to be the parent node, and the Destination field is set to be the NCU.
NCU to Node	NCU to Node messages are sent across multiple mesh hops using the DLCCH, where options exist to address to the whole mesh, to a zone, or to a specific device.
Child to Parent	Child to Parent messages are sent between neighbouring nodes using acknowledged RACH messages, where the MAC Destination and the Destination fields are both set to the address of the parent node.
Parent to Child	Parent to Child messages are sent between neighbouring nodes using acknowledged RACH messages, where the MAC Destination and the Destination fields are both set to the address of the child node.

(Note that the terms parent and child above can also refer to “candidate” parent and child nodes, which are described later).

Where events occur that affect multiple RBUs (e.g. during mesh forming, or mesh re-forming in the event of multiple RBUs losing a common parent) then this could result in multiple devices transmitting simultaneously on the RACH, resulting in collisions and additional packet delay. Such cases are handled by time-multiplexing the times at which each device can send a new message over the RACH channel: this time-multiplexing is achieved using a virtual channel, the DULCH, which is mapped onto the RACH channel.

2.1 Introduction to DULCH Channel

The DULCH channel will be used for the following messages, and will add them to the queue for the primary or secondary RACH on the DULCH access slot (SAS) applicable to the unit:

- Status Indication
- Route Add
- Load Balance

A complete list of all messages is given in Table 4.

The Load Balance message uses the RACH in the downlink direction and is terminated at the child node without forwarding. The addressing scheme will set the MAC Destination and the Destination fields both to the address of the Child Node. It will require each mesh node to accept the Load Balance message for all of its parent nodes in addition to those of its child nodes.

This is a slight departure from the existing convention, since to date we have used DLCCH exclusively for the downlink and RACH exclusively for the uplink. However, the RACH is ideal for neighbour to neighbour communications, and the direction of message transfer is actually immaterial.

Certain messages are defined that can only be transmitted in each device’s DULCH Access Slot, which is a unique slot for each device within the TDM structure and is defined in the next section. By making the DULCH Access Slots sufficiently sparse within the TDM structure, the amount of traffic entering the mesh can be controlled to levels that will significantly limit the number of likely collisions. (Note that other devices cannot send a message in another device's DULCH Access Slot.)

2.2 Delayed Uplink Channel (DULCH)

The Delayed Uplink Channel (DULCH) is a logical channel that sends messages over the Secondary RACH physical channel.

The services provided by the DULCH are identical to those provided by the equivalent RACH, except that the opportunities for an RBU to transmit a new message into the mesh are significantly restricted in order to prevent mesh congestion. Slots in which the RBU is permitted to send a new message are called DULCH Access Slots (SAS), and are defined Section 2.3. (Note that some of the mesh healing processes are also initiated in the DULCH Access Slot).

Once a DULCH message has sent on a RACH channel, other nodes will handle it exactly as they would any other RACH messages (e.g. sending and receiving acknowledgements, and using random back-off retransmissions): the term "Scheduled" only describes the opportunities for an RBU to place the message into the RACH queue.

As with all messages going over the RACH channel, it is possible that the new DULCH message will collide with a RACH message already being propagated across the mesh, in which case both messages will require re-transmission using random back-off.

2.3 Delayed Access Channel (DULCH) Access Slot (SAS)

A DULCH Access Slot (SAS) is used when multiple RBUs are asked or scheduled to generate a RACH message. Typically, this happens during mesh forming, or when the NCU sends out a mesh-wide or zone-wide status request, or during mesh healing when multiple child nodes need to rapidly respond if they lose a common parent. The DULCH Access Slots are defined to be infrequent, thus preventing the build-up of messages within the mesh to limit collisions, re-transmissions and possible loss of messages.

The mapping of DULCH messages onto the DULCH Access Slots is described in Section 5.2.

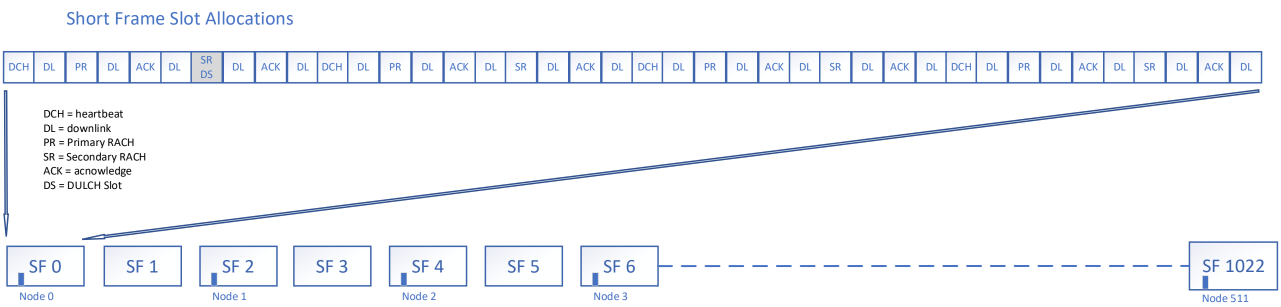


Figure 1: DULCH Access Slots

2.3.1 DULCH Access Slot

Each device on the mesh network is assigned a dedicated uplink channel (DULCH) on which no other device may transmit. This ensures that each device has an opportunity to transmit without competition from other devices. The purpose of the DULCH is to relieve network congestion at busy times by spreading the messages out over a period of time.

The slots are allocated by network address. The DULCH slot replaces the first S-RACH slot (slot 6) in every second short frame. Each device is allocated a short frame to transmit in using the formula:

Short frame = Network ID * 2

This results in a DULCH slot in slot 6 of every even numbered short frame. Odd numbered short frames have a standard S-RACH slot. This is shown in the figure above.

2.3.2 DULCH Interval

The standard interval between consecutive DULCH slots for a particular device is 1024 short frames, 25 minutes 49 seconds.

DULCH WRAP

On most systems there will be less than 511 devices on the mesh, and DULCH WRAP is introduced to reduce the interval between DULCH opportunities.

DULCH WRAP is a configurable property and can be set to accommodate the actual number of devices on the mesh using the formula:

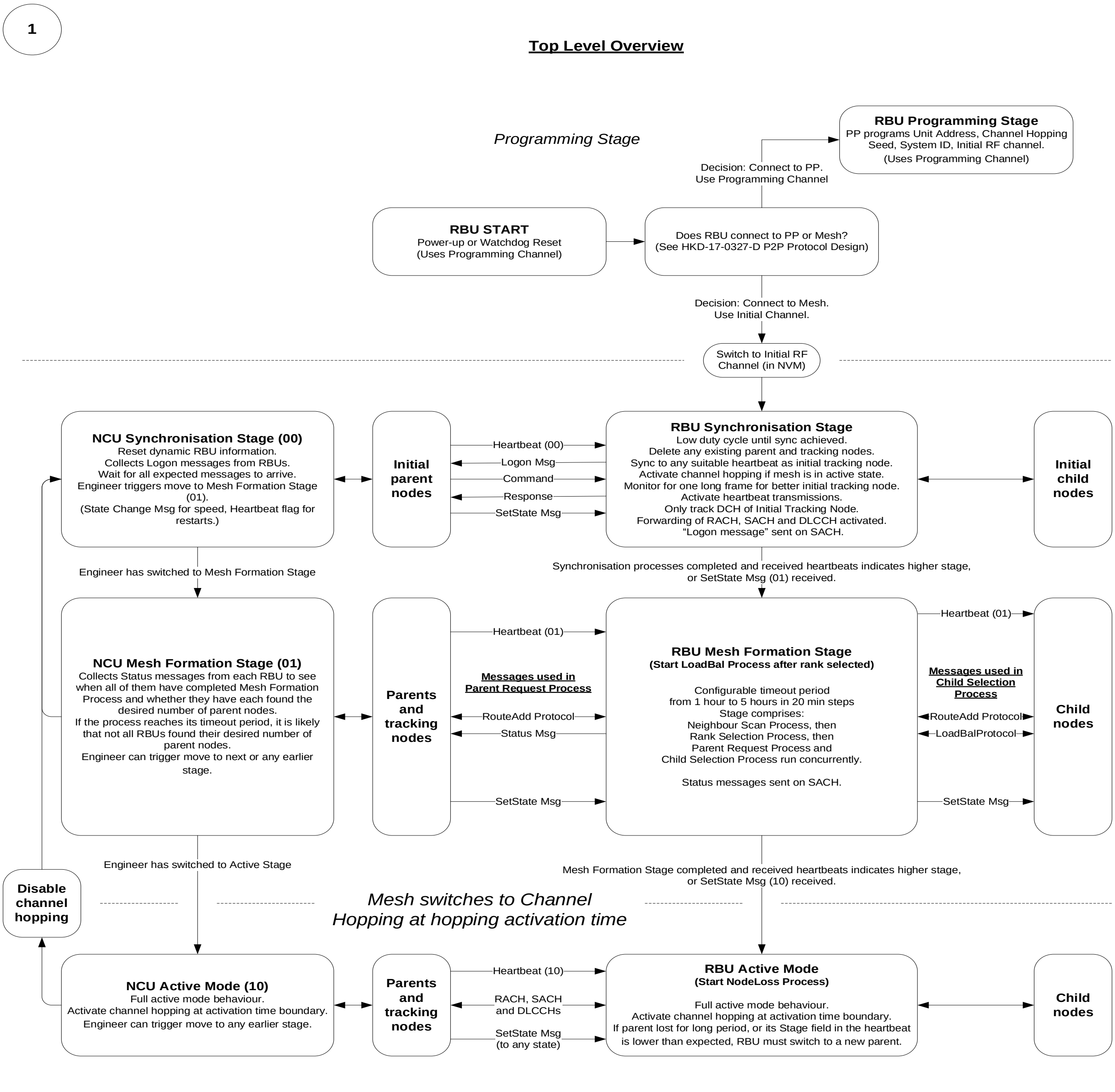
DULCH WRAP = 2 * (max unit address + 1)

For example, a system with 15 devices can be assigned a DULCH WRAP of 32 short frames. All 15 devices will have a DULCH slot in short frames 0 to 31, the cycle then wraps around enabling a second DULCH slot in short frames 32 to 63, a third in short frames 64 to 96 e.t.c.

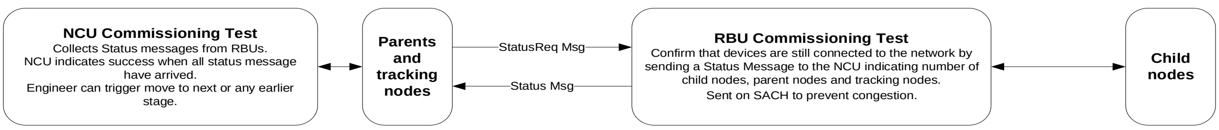
This reduces the DULCH interval to 32 short frames, 48.4 seconds.

3 MESH FORMING

The diagram below is the top-level overview of the mesh forming and healing process.



"Commissioning Test" is a general status request that can be run at any time after Synchronisation Stage has complete



3.1 `Mesh Formation

In order to form a mesh, an RBU must go through the stages shown in Figure 2. These stages are coordinated across the mesh by messages sent on the DLCCH from the NCU, and supplemented (for devices re-joining the mesh) by a State field in the heartbeat.

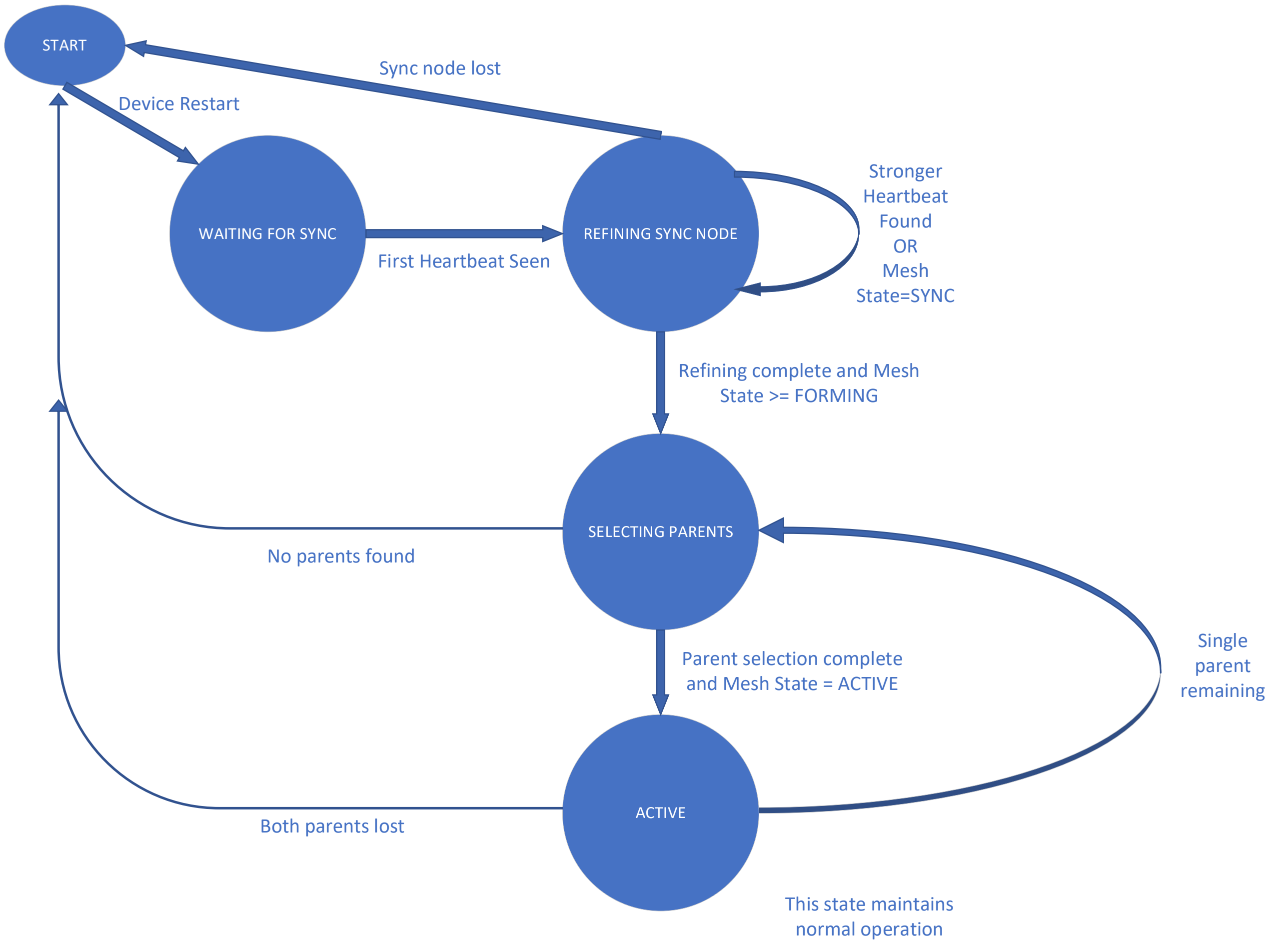


Figure 2 Modes and Stages of the Mesh Forming Activity

3.1.1 Programming Stage

In this stage the RBU is connected to the Portable Programmer (PP) and is programmed with the information that uniquely describes the mesh and the RBU's identity within it.

After programming, there are two scenarios in which an RBU can enter a mesh. In the first scenario, the mesh is initially turned Off (see glossary): the RBUs will initially spend most of their time in a low power state, waking occasionally to detect a heartbeat that would signify that the mesh has been switched to On. In the second scenario, the mesh is On (see glossary): the RBUs will detect the current stage of formation of the mesh by reading the State field from the heartbeat messages and will automatically switch from the Synchronisation Stage to the

Mesh Formation Stage, then perhaps to the Active Mode, until it has reached the same stage as the rest of the mesh.

In the descriptions of each stage below, the first scenario (Mesh Off) is described first, and is followed in each case by a short description of how the behaviour changes for the second scenario (Mesh On).

3.1.2 Synchronisation Stage

When an RBU is turned on, it should first listen using continuous reception for a period of at least equal to the DCH channel hopping repeat interval in order to see if it is re-joining an existing mesh. If it detects such a mesh then operation continues as described below, without entering the low-duty-cycle mode.

If the RBU does not detect a mesh within the period described above, it moves to a low-duty-cycle, low-power mode, waking occasionally to try and detect a heartbeat message from the mesh it has been programmed to join. Whilst the mesh components are being installed the RBUs will initially not receive any heartbeats, and so the RBUs will spend the majority of their time in low-power mode, minimising their power consumption whilst the mesh components are being installed. The low-duty-cycle behaviour is characterised in Table 1 below.

Table 1 Description of the three stages in the low-duty-cycle, low-power mode

Stage of Cycle	Duration	Description
Stage 1 Initial Listening Period	72Hrs (configurable)	The RBU initially listens for heartbeats on the initial channel for a configurable duration.
Stage 2 First Sleep Cycle	14 Days (Configurable) of listening (30 minutes) and sleeping (3Hrs, configurable)	After the initial listening period has expired, the RBU enters a cycle of sleeping for 3 hours (configurable) and listening for 30 minutes. This stage lasts for 3 days (configurable).
Stage 3 Second Sleep Cycle	Indefinite period of of listening (30 minutes) and sleeping (6Hrs, configurable)	When stage 2 has expired with no network detected the RBU enters stage 3, and indefinite period of sleeping for 6 hours (configurable) and listening for 30 minutes.

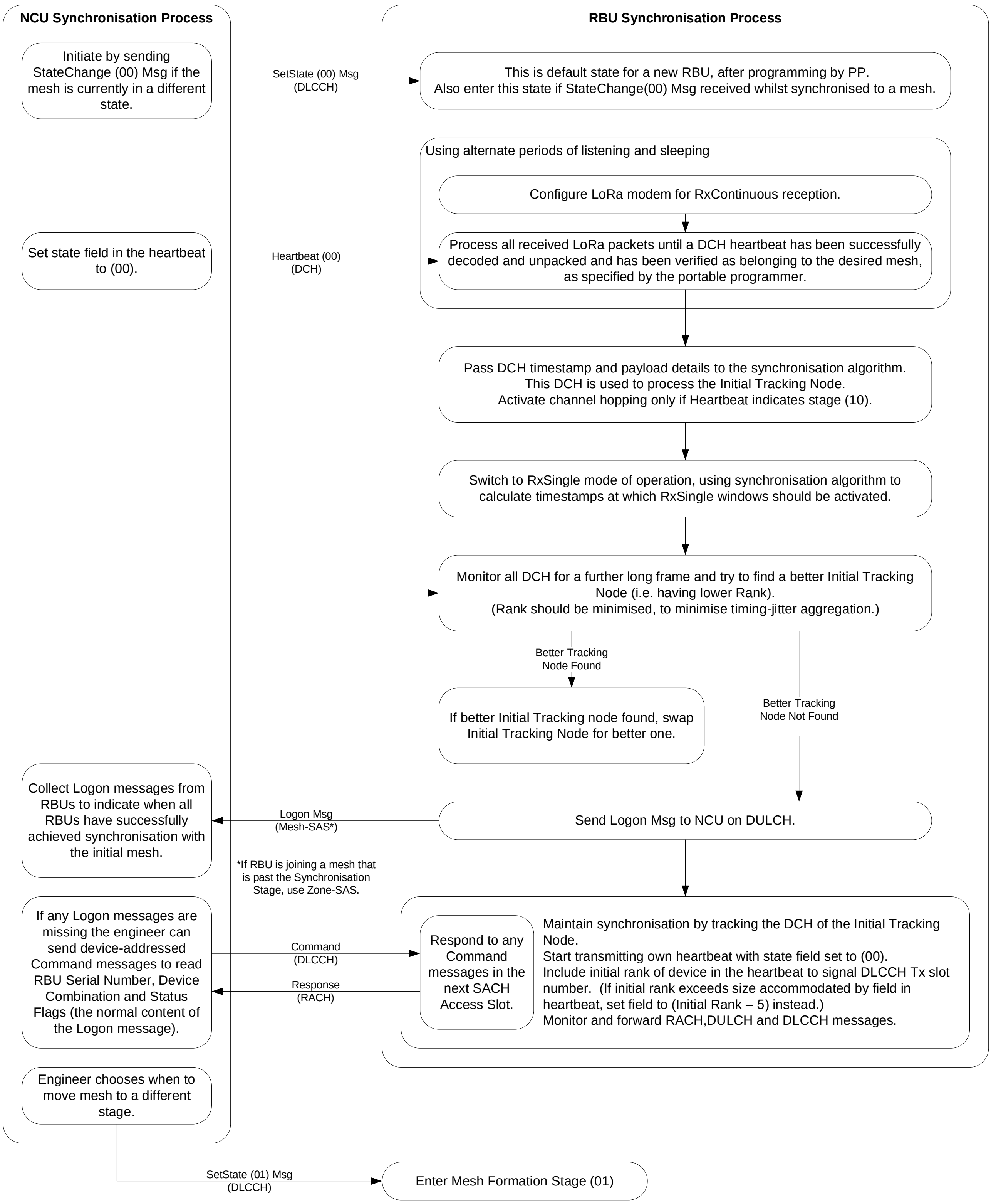
When the mesh is ready to be formed, the NCU is instructed to generate and transmit its heartbeat. On detecting this heartbeat, which is uniquely associated with this mesh, some RBUs will detect it, will time-synchronise to it, and will use it as their Initial Tracking Node. RBUs continue to listen to other DCH slots for a further long frame to see if they can find a better Initial Tracking Node, i.e. one that has a lower rank, and therefore has fewer hops to reach the NCU, or the same rank but higher signal quality. If a new initial tracking node is found, the monitoring resumes for a whole additional long frame, to see if any further reduction in rank becomes possible.

Once an RBU has synchronised to the mesh it starts to transmit a heartbeat, but it signals in the rank field of the heartbeat that it hasn't currently selected its rank value.

When an RBU Joins a Pre-Formed Mesh (Mesh "On" Scenario)

If an RBU joins or re-joins an existing mesh and finds that the mesh has already passed the Synchronisation Stage, the RBU does not wait for the NCU to issue a SetState message, but instead moves straight to the Mesh Formation Stage . If the mesh is in the Active Stage (indicated by the State field in the DCH) then the RBU must enable Channel Hopping.

Synchronisation Stage



3.1.3 Mesh Formation Stage

The Mesh Formation stage must run synchronously in all elements of the mesh, and is therefore scheduled to start at the beginning of the next Long Frame (see Section 3.2). After entering the Mesh Formation stage, the RBU will follow these processes.

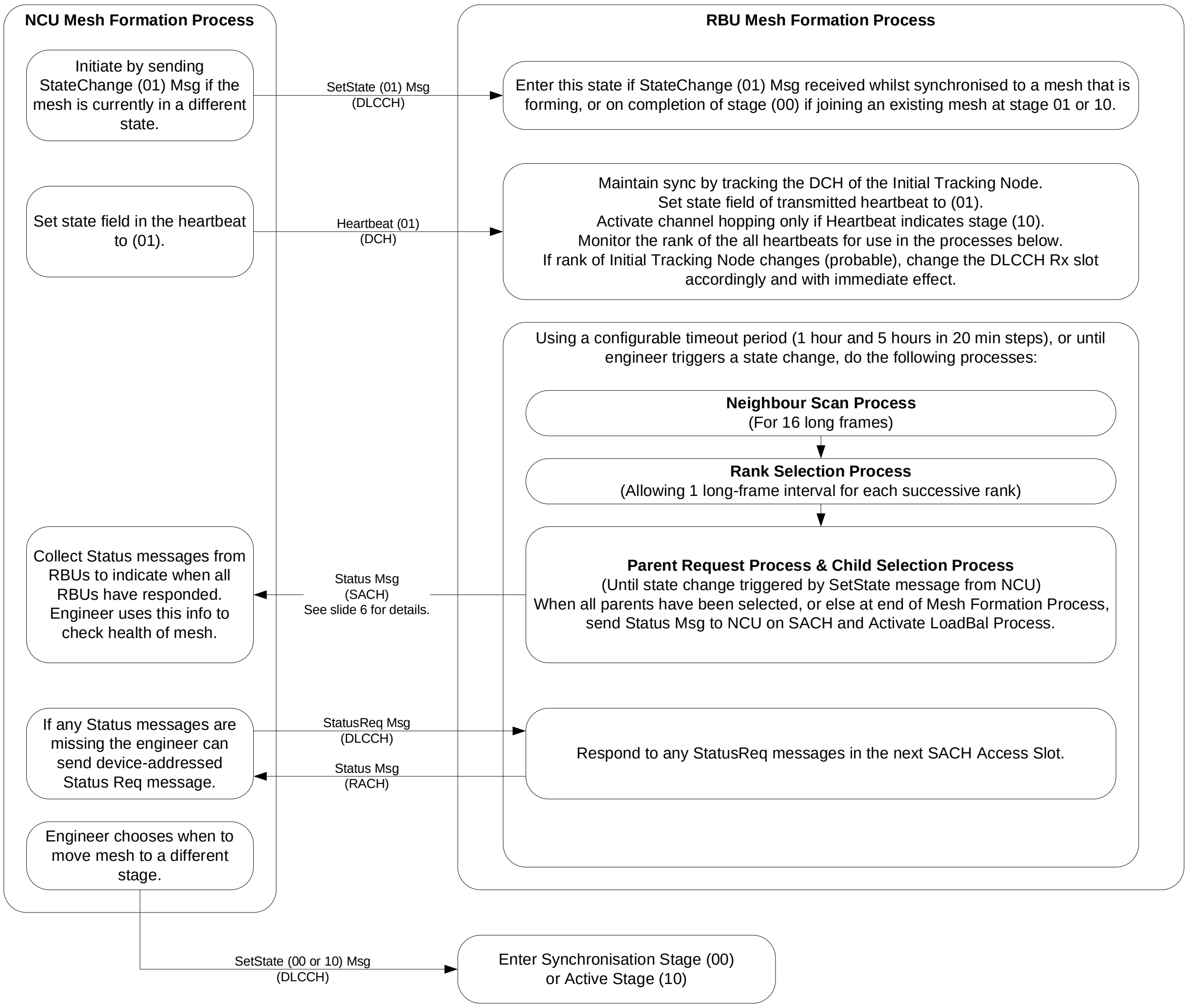
- Neighbour Scan Process
- Rank Selection Process
- Load Balancing Process is Enabled (background task)
- Parent Request Process & Child Selection Process

The Parent Request Process and the Child Selection Process effectively mirror each other in their functions

- The Parent Request Process is performed by a node seeking to become a child to another RBU. Requests for a device to become a parent are signalled using a RouteAdd message.
- The Child Selection Process is the concurrent process running in the candidate parent that handles the responses to incoming RouteAdd sent by the Parent Request Process by simply choosing whether to accept or refuse any received parent requests (see Section 3.3 "RouteAdd Process").

The Load Balancing Process essentially runs as a background task after the rank has been selected, and continues beyond the Mesh Formation stage, running throughout the Active Mode too. It is described in Section 4.1.

Mesh Formation Stage



Neighbour Scan Process

The Neighbour Scan Process runs for two long frames after selecting the initial tracking node. Each RBU will average the DCH SNR value of every mesh node it can successfully detect. At the end of this process, the RBU will know which of its neighbours are above the permitted threshold to be a parent node.

See diagram "Neighbour Scan and Rank Selection" in HKD-17-0329-D Mesh Forming.vsd.

Rank Selection Process

After the Neighbour Scan Process has completed the RBU examines the collected heartbeat data, seeking the best candidate parents.

The NCU is always favoured as parent if its signal meets the quality criteria for joining (See table below).

If the NCU is not a viable candidate the RBU will seek the lowest rank at which it can see two parents. It will also identify two tracking nodes if they are available. These are held in reserve as replacements for candidate parents that don't accept the RBU as a child.

In the event that the RBU fails to find two parents of the same rank, it will search for the lowest rank at which a single parent can be found.

Signal quality criteria must be met for accepting candidate parents. This requires a minimum SNR of +5 (Radio manufacturer's recommendation) and a signal strength that is at least 15dB above the radio sensitivity for single parent connections and 10dB above for two-parent connections. A further minimum attenuation reserve of 10dB is added to determine the acceptance threshold.

The sensitivity of the Cygnus2 radio is -132dBm, giving the acceptance criteria in the table below.

	Single Parent Connections	Two-parent Connections
RSSI	-107dB	-112dB
SNR	+5	+5

Parent Request Process

Having identified candidate parents the RBU will send a ROUTE ADD message to the selected primary parent on the DULCH channel. The message will be repeated if the candidate parent fails to acknowledge receipt. The candidate parent responds on the S-RACH channel with two ROUT ADD RESONSE messages, confirming that the link has been accepted by the parent and passing system configuration data (day/night, zones enabled etc.). Two messages are required to pass all the configuration properties.

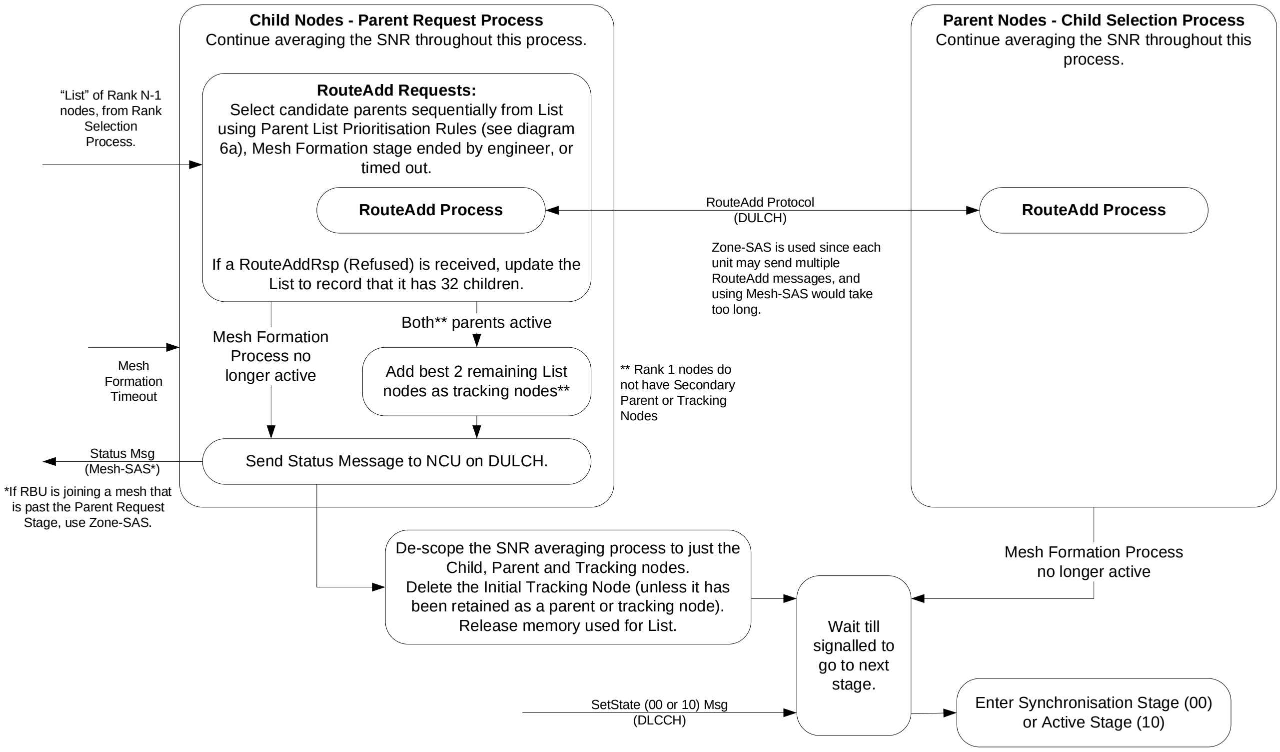
If the candidate parent declines the link the RBU discards it as a candidate and promotes the secondary parent candidate to primary, and the first tracking node to candidate secondary parent. A ROUTE ADD message is then sent to the new primary candidate.

Once the primary parent has accepted the link, the ROUTE ADD process is repeated for the secondary parent.

Child Selection Process

The Child Selection Process is how a candidate parent responds to the Parent Request Process. It is currently entirely defined by the RouteAdd Process (see Section 3.3).

Parent Requests and Child Selection



Parent Selection Process

The parent selection process during mesh forming operates as follows. The neighbour list is examined for the best candidate nodes with the requisite rank and SNR, using the following prioritisation rules:

1. Only select if RSSI and SNR are above acceptance threshold.
2. Prioritise node with fewest No. of Children. Do not select a node having the maximum number of children.
3. Units having the same no of children are prioritised in descending order of SNR. (The SNR and No of Children are updated with each received heartbeat.)

Then the following nodes are added to the synchronisation algorithm in descending order of priority:

1. Primary Parent
2. Secondary Parent
3. Primary Tracking Node
4. Secondary Tracking Node.

These nodes are then used by the synchronisation algorithm until and unless a Parent Replacement instruction is received from the Session Manager (e.g. if a parent node sent a ROUTE ADD RESPONSE signalling that it declined the request). Note that the Session Manager will only issue a Parent Replacement instruction for a node that has been requested as a parent – the Session Manager will not request the replacement of a tracking node that is not a parent node.

Parent Replacement Process

The Session Manager may decide to delete a parent node, and for a substitute parent be allocated: this might happen for example if the node signalled "declined" in its response to a RouteAdd message.

If a parent is replaced, the following procedure is applied:

1. The parent signalled by the Session Manager is deleted from the synchronisation algorithm's list of tracking nodes.
2. The parent node that has been deleted is marked in the Neighbour List as unavailable to the Parent Selection Process.
3. The Session Manager is notified that the primary tracking node is promoted to replace the parent node. It will then initiate the Parent Request process with that node.
4. A new neighbour scan is run for a duration of one full long frame, during which time the RSSI and SNR of all detected nodes is recorded.
5. The best available nodes at the requisite rank and SNR are added to the synchronisation module to bring the total number of devices being tracked to 4, or fewer if only restricted options are available.

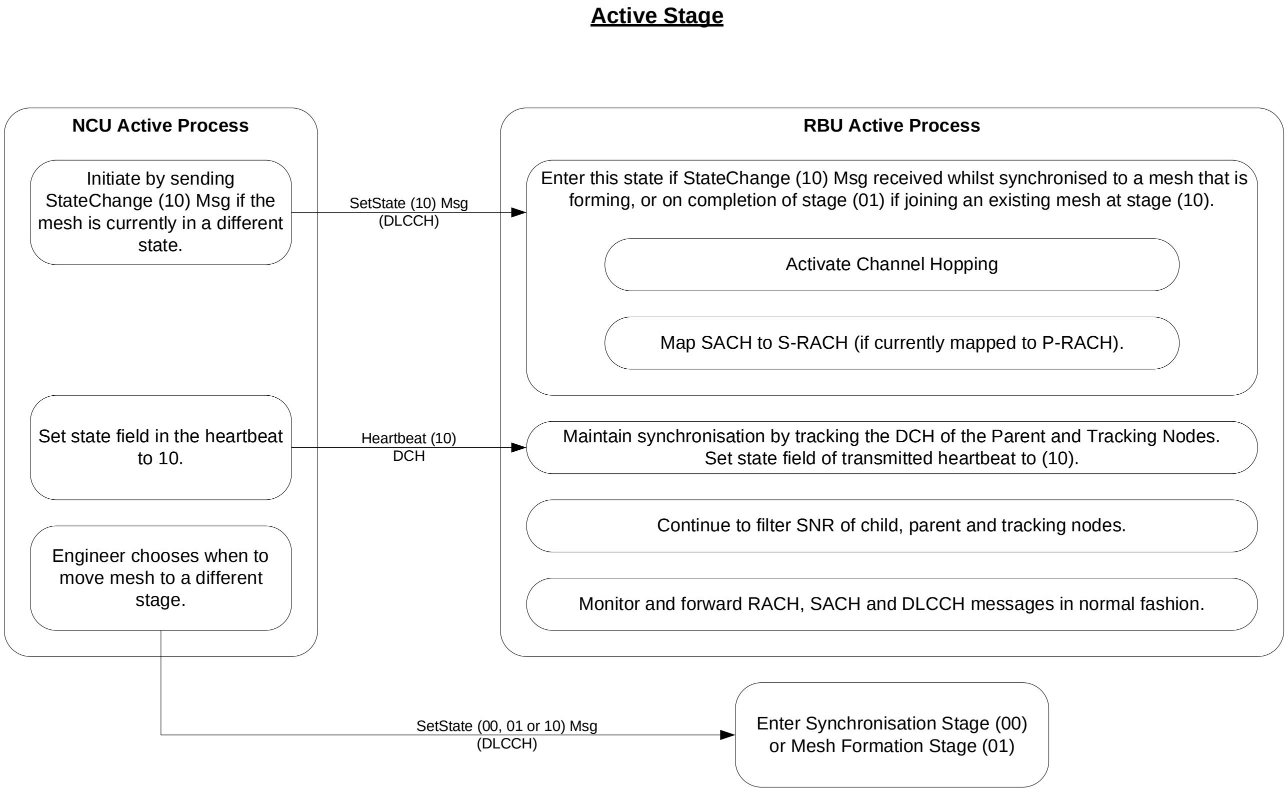
When an RBU Joins a Pre-Formed Mesh (Mesh "On" Scenario)

If an RBU joins or re-joins an existing mesh and finds that the mesh has already passed the Mesh Formation Stage, the RBU does not wait for the NCU to issue a SetState message, but instead moves straight to the Active Mode on completion after issuing the Status message described above. If the mesh is in the Active Stage (indicated by the State field in the DCH) then the RBU must enable Channel Hopping.

3.1.4 Active Mode

The Active Mode follows on completion of the Mesh Forming process. The main activities in the Active Mode are:

- Channel Hopping is enabled. (See HKD-17-0076-D Software Architecture and Design Specification, Section 3.3.2.)
- Mesh Healing Processes are started. (See Section 4.)
- Synchronisation with the mesh is maintained by tracking the DCH heartbeats of its synchronisation node, normally the Primary Parent.
- The SNR of all parent nodes, child nodes and tracking node is monitored. A low pass filter is applied to each to remove the immediate effect of fading on the measured SNR.
- RACH and DLCCH messages are monitored and forwarded as required.



3.2 Mesh-Synchronised Activation Times

When processes must be started synchronously by all RBU within the mesh, the activation time will always be the first slot in a new Long frame. It is the responsibility of the NCU to broadcast instruction to perform these synchronised activities sufficiently in advance of the beginning of the next long frame to ensure that all RBUs have received the instruction in time to start synchronously, rather than some starting at the beginning of one Long Frame and others starting at the beginning of the subsequent long frame: for this reason such a broadcast message should not be sent by the NCU if there are fewer than 16 short frames until the start of the next long frame, but should instead be deferred until the next long frame has started.

3.3 RouteAdd Process

The RouteAdd process is the process by which a child node asks a candidate parent node to be its parent. This has widespread use in the Mesh Forming and Healing processes.

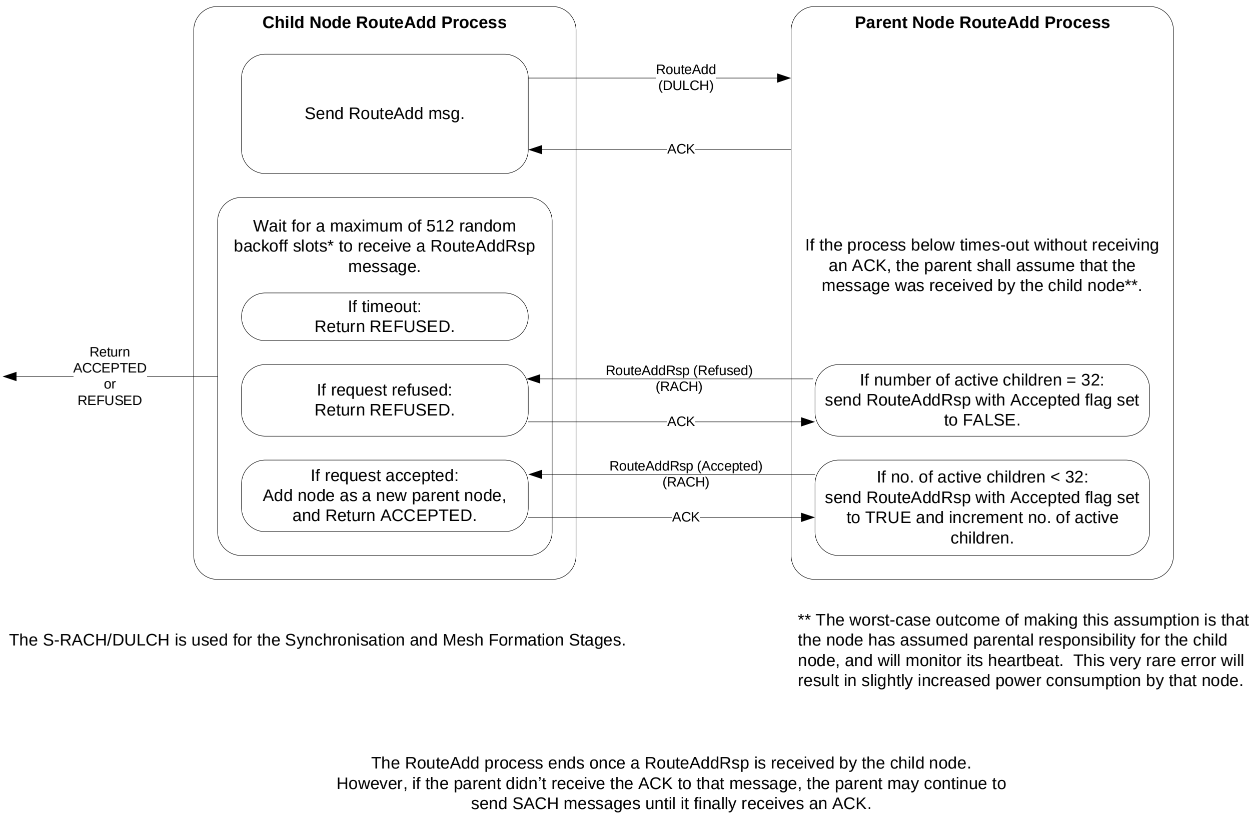
If a child wishes to ask another node to be its parent, it sends that node a RouteAdd message. Typically it does this having first decided that the candidate parent has some vacancies for additional children, based on the number of child nodes it signals in its heartbeat.

The candidate parent node must respond with either RouteAddAccepted or RouteAddRefused.

- RouteAddAccepted is sent if the node currently has fewer than the maximum permitted number of child nodes. In this case, the child node adds the requested node as a Parent, and the parent adds the requesting node as a child.
- RouteAddRefused is sent if the node has its full quota of children. (Note that if it were known upfront that the candidate parent had its full quota of child nodes, the RouteAdd request would not have been sent. However, since the heartbeat

is only sent once per long frame signalling the number of child nodes, the information held by the prospective child node may be out of date.)

RouteAdd Process



3.4 Content of the Status Message

The Status message is used to a) demonstrate that each RBU is connected to the mesh, and b) to transfer the following information to the NCU (if available or applicable when message is sent):

- Primary Parent ID
- Secondary Parent ID
- Averaged RSSI of Primary Parent
- Averaged RSSI of Secondary Parent
- Number of tracking nodes
- Number of Child Nodes of Primary Tracking Node
- Rank
- Status Event
- Status Event Node
- Faults/warnings indication

3.5 List of Parameters from Portable Programmer

The portable programmer must program the RBU with the following information, for support of Mesh Forming/Healing. Program of additional information may also be required for the operation of the RBU, however, those parameters are outside of the scope of this document.

- Unit Address = 1 to 511 (Unique address in the system)
- Zone Number = 1 to 96
- Channel Hopping Seed
- System ID
- Initial RF channel
- MaxDurationOfMeshFormationProcess = Based on formula described in section

4 MESH HEALING

Mesh healing is activated per RBU on completion of the Mesh Formation process, at the point at which the Status Message is sent to the NCU. Figure 3 shows a flow chart of the top-level behaviour in Active Mode, including the Mesh Healing activities "Node Loss Process", "Associated Node Loss Process" and "Load Balancing Process". The behaviour is cyclic (i.e. with different behaviours occurring at defined opportunities within each short frame) and is largely driven by messages received on the different logical channels.

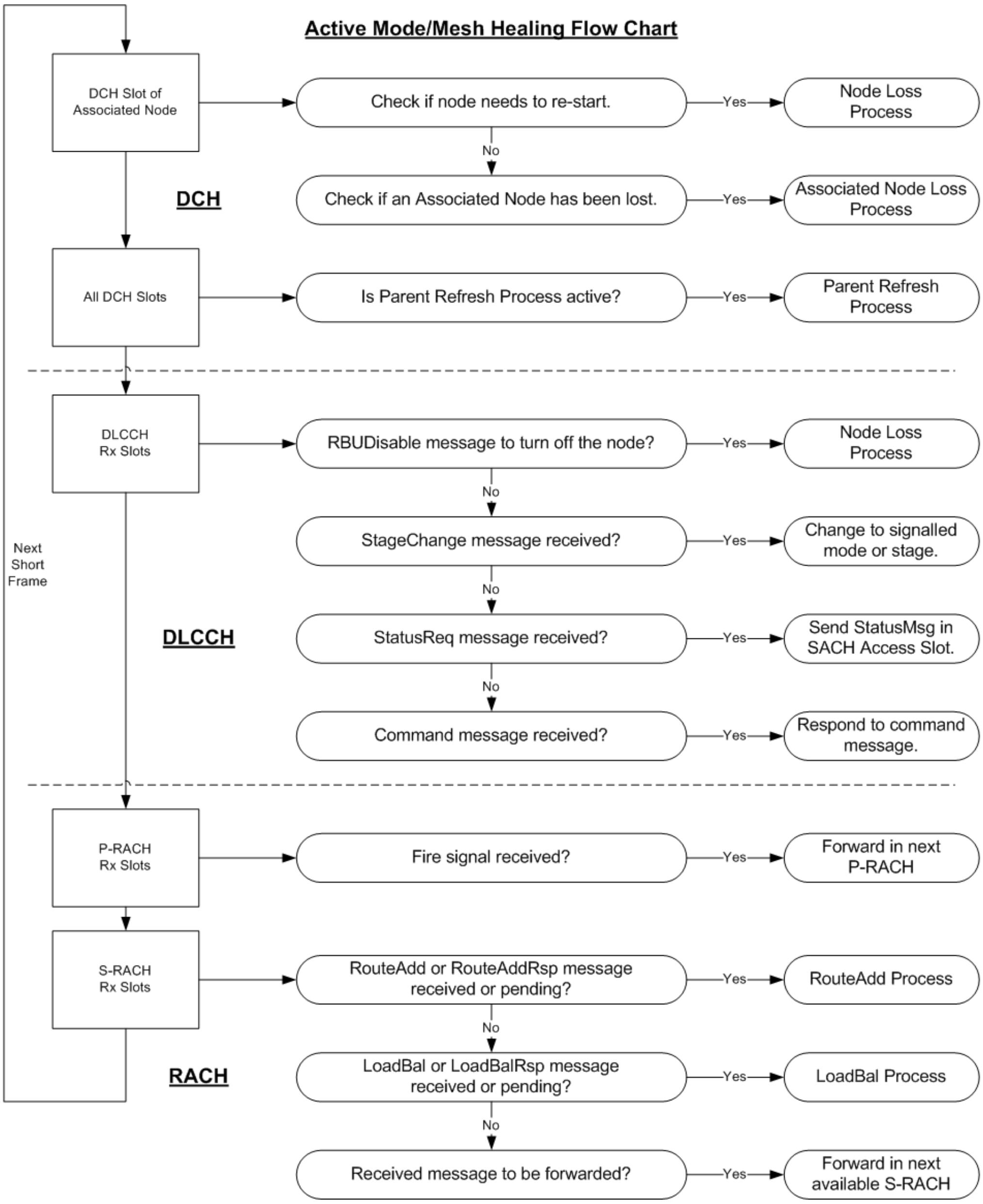


Figure 3: Active Mode and Mesh Healing Flow Chart

Mesh healing is implemented using a set of processes that collectively maintain the health of an existing mesh.

- Load Balancing Process: moves children from heavily-loaded to lightly-loaded parents.
- Node Loss Process: handles the case of nodes leaving the mesh, rapidly replacing lost parents with existing tracking nodes.
- Parent Refresh Process: refreshes depleted lists of parent and tracking nodes: it is called from the Node Loss Process, rather than running independently.

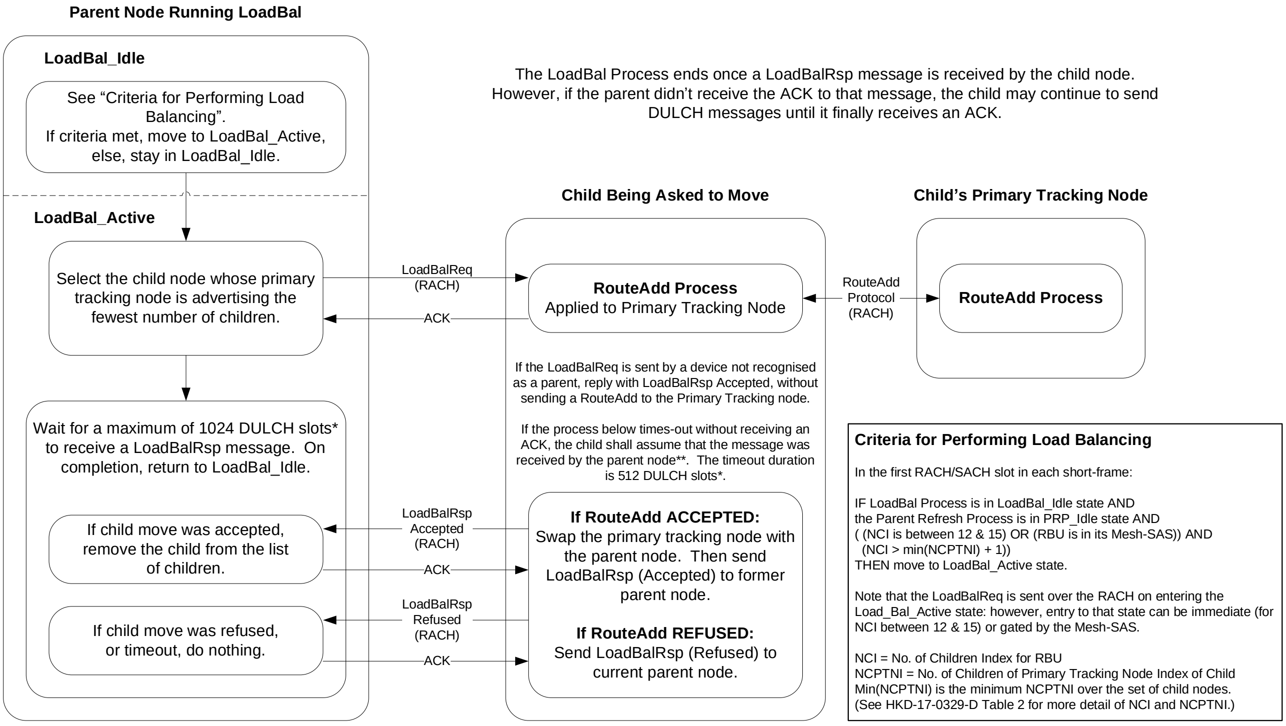
4.1 Load Balancing Process[1]

Load balancing is a process in which parent nodes with large numbers of child nodes negotiate the transfer of some of their children to other candidate parents that have fewer children. It is used infrequently, only when the parent node reaches its SACH Access Slot, and as per all Healing activities it is activated per RBU on completion of the Mesh Formation process, at the point at which the Status Message is sent to the NCU. Each time it is called, the parent is allowed the chance to ask just one of its children to move: the child who is signalling the Primary Tracking Node with the fewest number of children is chosen for this purpose. The child would respond positively if its new parent accepts it, or negatively if the new parent refuses it, signalling the response in the RouteAddRsp.

The Load Balancing Process is activated in each RBU once all the parents and tracking nodes have been added and the RouteAdd requests to the parents have been accepted. It is normally in the LoadBal_Idle state, and is regularly tested against activation criteria to decide whether it should enter LoadBal_Active state, whereupon it runs for one complete attempt to move a child to another parent, before re-entering the Load_Bal_Idle state.

[1] Note, Load Balancing has not been implemented at the date of release of this document.

Load Balancing Process



* These figures allow 256 DULCH slots timeout each for the LoadBalReq, RouteAdd, RouteAddRsp and LoadBalRsp messages.

** The worst-case outcome of making this assumption is that the former parent node still assumes parental responsibility for the child node, and will monitor its heartbeat. This very rare error will result in slightly increased power consumption by that node.

4.1.1 Criteria for Entering the LoadBal_Active State

In the first RACH/SACH slot in each shortframe, IF (LoadBal Process is in LoadBal_Idle state) AND (the Parent Refresh Process is in PRP_Idle state) AND ((NCI is between 12 & 15) OR (RBU is in its SACH Access Slot)) AND (NCI > min(NCPTNI) + 1)) THEN move to LoadBal_Active state.

where:

- NCI = No. of Children Index for RBU
- NCPTNI = No. of Children of Primary Tracking Node Index of Child
- min(NCPTNI) is the minimum NCPTNI over the set of child nodes.

See Table 2 for more detail of NCI and NCPTNI.

The significance of the NCI range from 12 to 15 is that these values of NCI signal that the device has a large number of child nodes (specifically, between 29 and 32 inclusive). In other words if the device has a large number of child nodes then it need not wait for the arrival of its SACH Access Slot in order to start the load balancing process.

If the entry criteria is because (NCI is between 12 & 15) then entry to the LoadBal_Active state is immediate and the LoadBalReq messages is sent in the next available RACH slot. If the entry criteria is because (RBU is in its DULCH Access Slot) then the RACH is still used, but the opportunities to send the messages are restricted to Mesh-SAS occasions because entry to the LoadBal_Active state itself is restricted to Mesh-SAS occasions.

The criteria ensure that for the RBU: IF the number of child nodes is 29, 30, 31 or 32 and with immediate effect, OR only in the DULCH Access Slot for any other value of NCI and with periodic effect, AND if the Parent Refresh Process isn't currently running AND if the value of NCI is at least 2 greater than the value of min(NCPTNI) THEN move to the LoadBal Active state. Using the "at least 2 greater than" criteria provides hysteresis, preventing two nodes from exchanging children back and forth on successive activations of their load balancing processes.

Timeout periods of 1024 and 2048 SACH slots are described in diagram "Load Balancing Process" above. In Configuration Mode SACH slots are the Primary RACH slots, and in ACTIVE Mode SACH slots are the Secondary RACH slots. The timeout of values 1024 and 2048 come from the worst possible time to ACK a message delivered using the RACH mechanism, which comes from the worst possible time to deliver the ACK to a message when random back-off retransmissions are scheduled 1, then 2, then 4, then 8, then 16, then 32, then 64, and then finally 128 slots later, giving a total worst case delay per message of 255 slots.

NCI Calcuation

The number of children index (NCI) can have a value in the range 0 to 15. The maximum number of children is a configurable property on the RBU and is mapped to NCI using the formula:

NCI = (15 / max_children) * number_of_children.

For some max_children settings this formula can produce a result of 0 when a single child is present. This situation is captured and the NCI is corrected to 1.

Table 2

4.2 Node Loss Process

There are two node loss process scenarios: the Node Loss scenario is when the node itself is shutting down or restarting; the Associated Node Loss scenario is when an associated node (a parent, child or tracking node) has been instructed to shut down, or its heartbeat is missing or of poor quality. The Node Loss Process has higher priority than the Associated Node Loss Process.

Additionally, the Node Loss and Associated Node Loss processes can either be NCU-Initiated (signalled using a RBU Disable message), or Locally-Initiated based on decisions made by the RBU itself.

1. Node Loss Process, NCU-Initiated
   - The RBU has received an RBU Disable message in which the Unit Address field contains the address of the RBU itself.
2. Node Loss Process, Locally-Initiated
   - The RBU has not heard the heartbeat of all its parents and tracking nodes,
   - Or if the average SNR[2] of all of its parents and tracking nodes is below the SNR Minimum Attenuation Reserve threshold,

[2] Note that each RBU maintains a filtered average SNR of all heartbeats that it is scheduled to receive.

- Or if the State field in both parents and all tracking node's heartbeats is lower than that of this RBU.

3. Associated Node Loss Process, NCU-Initiated

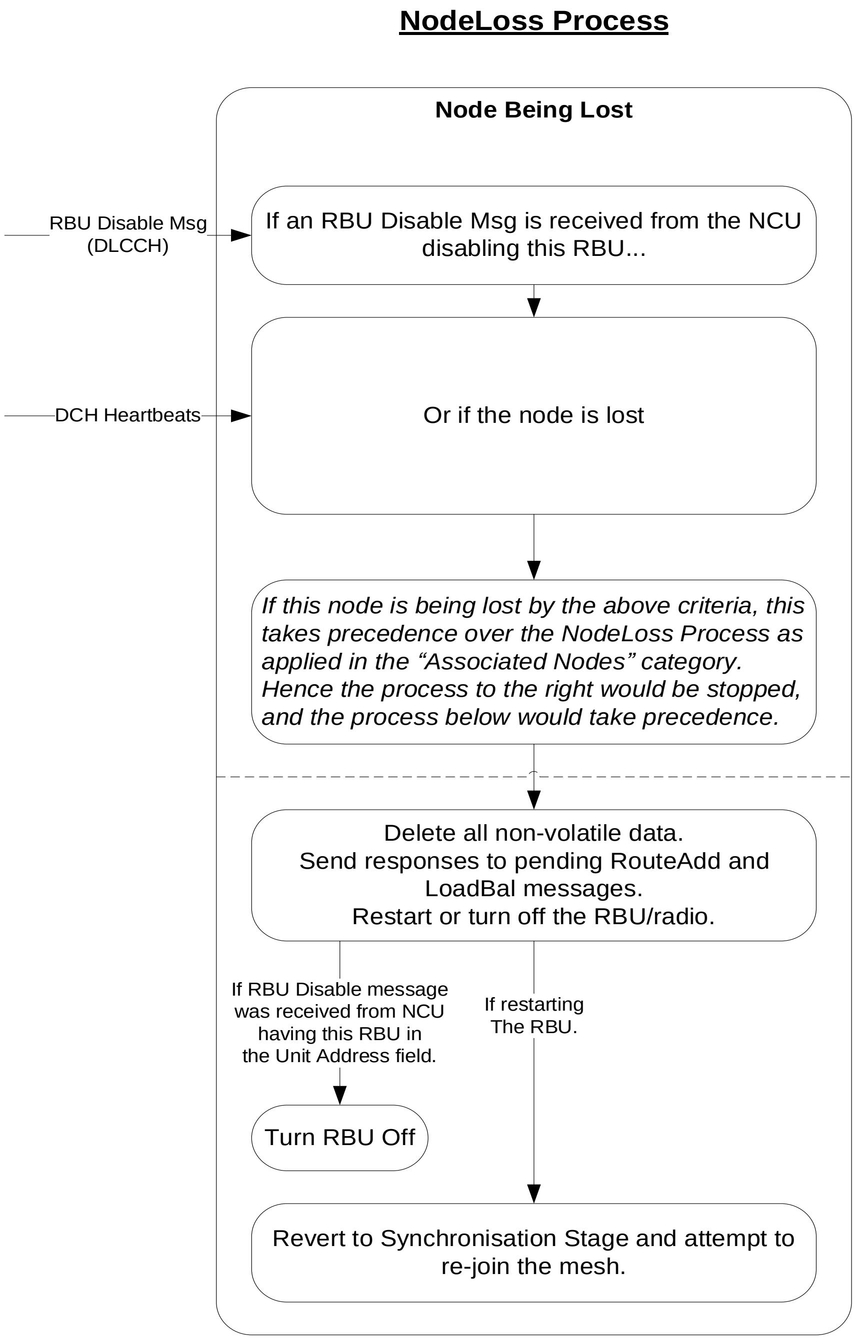
   - The RBU has received an RBU Disable message in which the Unit Address field contains the address of an associated node (a parent node or tracking node of the RBU). If the RBU Disable message is targeted at one of the devices child nodes, the RBU does not run the Associated Node Loss process. Instead, the parents continue to monitor the child's heartbeat, which should stop immediately: on missing three consecutive heartbeats the parents will notify the NCU of the loss of the child node, in accordance with the Locally-Initiated Associated Node Loss Process described immediately below. By receiving these notifications, the NCU thus receives confirmation that the device has disabled itself.

4. Associated Node Loss Process, Locally-Initiated

   - The RBU has not heard the heartbeat of one or more of its child nodes, or one or more but not all its parents and tracking nodes,
   - Or if the average SNR of one or more of its child nodes, or one or more but not all its parents and tracking nodes, is below the SNR Minimum Attenuation Reserve threshold.

An RBU is not permitted to change rank unless it is completely restarted (e.g. the Parent Refresh Process failed). In all cases, if an RBU is restarted, all its child nodes must switch to a new parent, which will be triggered when the child nodes detect the loss of the heartbeat from the RBU: the first choice for a new parent of any child node will be its Primary Tracking Node. If the RBU doesn't have any tracking nodes, the RBU ends up by having too few parent nodes, and a search for more candidate parents is undertaken.

The following diagrams depict the behaviour, which is also outlined in the sections below.



4.2.1 Node Loss Process (Shut-Down or Restarted)

A node can be shut-down when triggered by the NCU-Initiated Node Loss Process (bullet 1 criteria above), or reverted to the synchronisation stage when triggered by Locally-Initiated Node Loss Process (bullet 2 criteria above).

If the RBU shuts down it will stop all activity.

If the node re-starts it will:

- Delete all information relating to its child, parent and tracking nodes.

- Stop all existing scheduled transmissions, RACH re-transmissions and receptions.
- Attempt to re-join the mesh from the Synchronisation Stage.
- Whilst it is re-joining the mesh, it will not transmit its rank (i.e. it transmits a reserved value in the rank field that signals that it has not yet selected its rank) until it has completed the rank-selection phase.

Note that if a node meets the criteria for commencing the Node Loss Process, but which is already running the Associated Node Loss Protocol (described in Section 4.2.2), the Node Loss Protocol will be applied with full precedence.

4.2.2 Associated Node Loss Process

The conditions for starting the Associated Node Loss Process are defined in bullets 3 and 4 above.

If a child node, parent node or tracking node is lost, the behaviour differs slightly in each case.

Note that only one instance of the Associated Node Loss Process should be run on any one node at any time: the criteria for starting the Associated Node Loss Process need not be considered whilst the process is running in response to an earlier decision.

All Associated Nodes (Common Behaviour)

- Remove the lost node from the list of associated nodes.
- Stop receiving on the DCH slot associated with the lost node.
- Follow the actions below for Child Node is Lost, Parent Node is Lost, or Tracking Node is Lost.
- Send a Status message to the NCU in the next RACH slot (sent via an available parent node).

Child Node is Lost

If the child node is lost by a parent node:

- For Locally-Initiated losses, the parent sends a Fault Report to the NCU, signalling which node has been lost from the mesh.

Parent Node is Lost

If a parent node is lost by a child node:

- Promote any lower-ranking parent and tracking nodes by one position each, to fill the gaps.
- If a tracking node was promoted to become a parent node, use a RouteAdd process to request it to become a parent. If that request is refused then delete that node, and if another tracking node is available (i.e. the former secondary tracking node that was promoted to primary tracking node), promote it to become the parent and again use the RouteAdd process to request it to become a parent. Wait to receive its response.
- After completion of the above, if this node has only one parent, activate the Parent Refresh Process to try to find replacements for any vacant parent or tracking nodes.

- On completion of the Parent Refresh Process, use the RouteAdd process with any candidate parent to request it becomes a parent.

Tracking Node is Lost

If a tracking node is lost:

- If the primary tracking node has been lost and there is a secondary tracking node, promote the secondary tracking node to become the primary tracking node.

Loss of All Parent and Tracking Nodes

If a device loses contact with all of its parents or tracking nodes (i.e. it cannot hear their heartbeats or their average SNR is below the Minimum Attenuation Reserve:

- The unit shall restart and will undertake the full mesh forming process. Note that it will not attempt to signal the NCU that this is happening, since it has effectively lost all uplink communication with the mesh.
- Note that any children of this device will need to respond as per "Parent Node is Lost" above. If those children had this node as an only parent (generally not desirable) then they will have also have suffered "Loss of All Parent and Tracking Nodes", and they too will undertake this process. Generally the mesh should be maintained such that all devices have at minimum two parent nodes, and preferably should also have tracking nodes, so this condition should be rare and should already have been signalled to the NCU as a warning.

4.3 Parent Refresh Process

The Parent Refresh Process is used to refresh the list of available parent nodes and tracking nodes, where selection of parent nodes is prioritised above that of tracking nodes.

The Parent Refresh Process is not run continuously, but is called from the Node Loss Process whenever a Parent Node has been lost. (It has been specified as a separate process, since in principle it could also be called periodically to make up for any shortfall of parents and tracking nodes, though this is not currently implemented.)

The Parent Refresh Process is similar to (but simpler than) the processes used for Mesh Formation.

When triggered by a qualifying event, perform the following numbered Parent Refresh Process steps below. The qualifying events to initiate this process are:

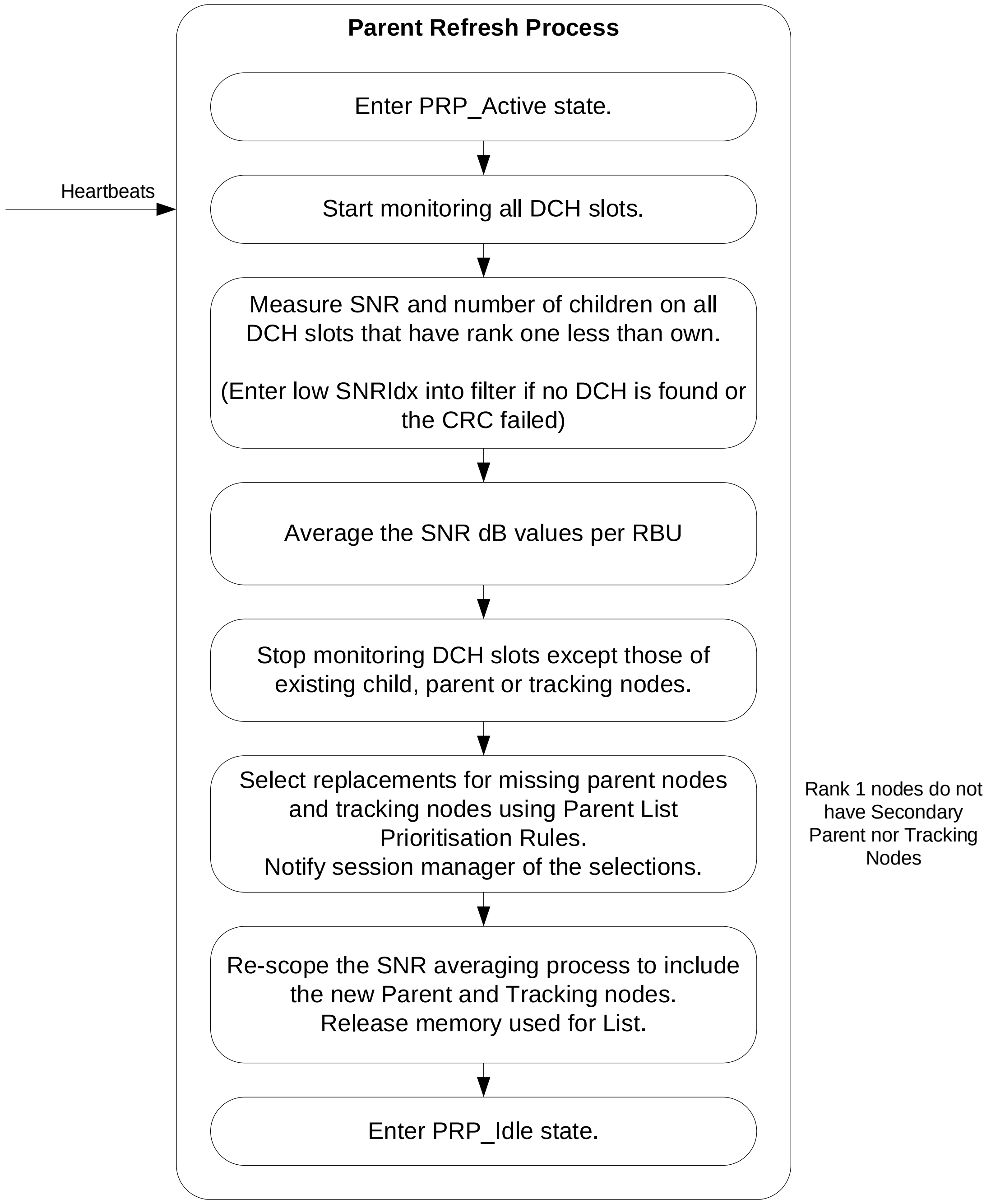
- Immediately when a parent node is lost and there is no tracking node to promote. (This can be initiated immediately, then the housekeeping of deleting the lost node can be performed once the parent refresh process has commenced.)
- Repeatedly again at intervals of 1000 long-frames if the number of parent nodes remains below 2.

1. Instruct the scheduler to receive on all DCH slots (which will include that of the lost node) for one complete long frame.
2. For all received DCH heartbeats having rank one less than the devices own rank, record the RSSI and SNR per candidate node.
3. Stop monitoring all DCH slots, excluding that of the existing parent.

4. Work through the detected candidate nodes and applying Parent List Prioritisation Rules to add first, any shortfall in parent nodes, and second, any shortfall in tracking nodes. Add the selected nodes to the synchronisation module as tracking nodes, and notify the session manager of the selections.
5. Re-scope the ongoing SNR averaging process to include the new Parent and Tracking nodes.

Parent Refresh Process

This process is activated on demand, from the NodeLoss Process.
Note that it can run for a very long duration before completing.



4.4 Prioritisation of Mesh Healing Processes

The processes have a prioritised hierarchy, as depicted in the diagram.

Mesh Healing Processes

Node Loss Process (highest priority)
(RBU Disable triggered in DLCCH slot)

If RBUDisable is received on DLCCH for this node:
1) Stop all other processes.
2) Send a RouteAddRsp (Refused) response to any pending RouteAdd request.
3) Send a LoadBalRsp (Accepted) response to any pending LoadBal request.
4) Turn off the RBU.

Node Loss Process
(RBU Restart triggered in DCH slot)

If heartbeats have not been received for all parents:
1) Stop all lower priority other processes.
2) Send a RouteAddRsp (Refused) response to any pending RouteAdd request.
3) Send a LoadBalRsp (Accepted) response to any pending LoadBal request.
4) Restart off the RBU.

Associated Node Loss Process and Parent Refresh Process
(Triggered in DLCCH or DCH slot)

If RBUDisable is received on DLCCH for an associated node, or if three consecutive heartbeats have not been received from the associated node:
1) Stop servicing the associated node and delete references to it in the RBU.
2) If lost node is a parent, attempt to replace it with one of the tracking nodes.
3) If lost node is a parent or tracking node, enter PRP_Active state (i.e. activate the Parent Refresh Process).
4) On completion of Parent Refresh Process, return to PRP_Idle state.

Load Balancing Process (lowest priority)
(Triggered in first RACH/SACH slot of short frame)

If Parent Refresh Process state is PRP_Idle, and other entry conditions are met, activate Load Balancing Process.
1) Enter LoadBal_Active state.
2) Select preferred child node to move and send it a LoadBal request.
3) Wait for response, or timeout.
4) Return to LoadBal_Idle state.

If a node is shut down by the NCU, any pending RouteAdd and LoadBal responses are sent, then the RBU ceases all activity.

- If a node restarts itself, any lower priority processes are stopped, then the RBU restarts.

- If a node activates the Associated Node Loss Process for a parent or tracking node, followed by activating the Parent Refresh Process, the Parent Refresh Process will block for its running duration any new RouteAdd request being sent by the Load Balancing Process. No other messages are blocked: this includes not blocking the reception of any RouteAddRsp responses currently pending from its own Load Balancing Process, nor their transmission in response to a RouteAddReq sent by another device.
- The Load Balancing Process has the lowest priority.

5 MESSAGES USED IN MESH FORMATION AND HEALING

The messages required to support the mesh forming and healing are as follows. All messages are passed on the Secondary RACH.

Each channel will have its own queue, and the messages will be served on a first-come first-served basis.

In Table 4, if the addressing mode is "Neighbour" then the message sent over the DULCH should not be forwarded by any node that receives it.

Table 3 Messages Used for Mesh Forming and Healing

Message Name	Contents
Heartbeat	See Section 5.3.
SetState	The states of the system are as follows. (State is a generic term we have adopted to cover terms including Mode and State.) 00 Synchronisation State (Configuration Mode) 01 Mesh Formation State (Configuration Mode) 10 Active Mode 11 Test Mode
RouteAdd	Primary or secondary parent request
RouteAddRsp	Accepted Flag (False = Refused) Day/Night setting Global Delay Enabled setting Enabled Zones Faults Enabled setting Global Delay override setting
LoadBalReq	
LoadBalRsp	Accepted Flag (False = Refused)
StatusReq	Device No, Zone No or Mesh-wide
RBUDisable	Device No.
StatusMsg	See Section 3.4.

Table 4: Updated Table 21 for 2001-SPC-0012-01 Mesh Protocol Design.docx

5.1.1.1 Message Type	5.1.1.2 Message Name	5.1.1.3 Dir	5.1.1.4 Channel (Config)	5.1.1.5 Channel (Active)	5.1.1.6 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[3]	Individual
8	App Firmware	Downlink	N/A	DL-CCH	Individual, Zone or Global
9	Route Add	Uplink	S-RACH	S-RACH	Neighbour
10	Route Add Response	Downlink	S-RACH	S-RACH	Neighbour
11	Route Drop[4]	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	Acknowledgemen t	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

5.2 Mapping of SACH Messages onto SACH Access Slots

The SACH messages are sent in the SACH Access Slots indicated below.

Logon

- The Logon message is obsolete, its purpose is fulfilled by the initial status indication message.

Status Indication

- If an RBU is part of a mesh that is currently forming and is at the same stage of formation as the rest of the mesh, it will send Status Indication messages in the DULCH.
- If an RBU has restarted and is re-joining an existing mesh, and its stage of formation is currently behind that of the rest of the mesh, it will send Status Indication messages in the DULCH.
- If an RBU is reporting at completion of the NodeLoss Process, is will send Status Indication messages in the DULCH.

RouteAdd

- If an RBU sends a RouteAdd message to create a new parent it will send it in the DULCH.
- If an RBU sends a RouteAdd message to replace a lost parent it will send it in the DULCH.

LoadBalReq

- The LoadBalReq message is always sent in the DULCH.

5.3 Heartbeat Message

The Routing Information field in the heartbeat (see HKD-16-0015-D Mesh Protocol Design, Section 7.2.1) contains the following fields:

- Slot Index: 19 bits (Bits 0-4 index in short frame, bits 5-12 index in long frame, Bits 13-18 index in super frame)
- State: 2 bits
  (00 = Synchronisation Mode, 01 = Mesh Formation Stage, 10 = Active Mode)
- Rank: 6 bits
  Used in the Synchronisation Stage and the Load Balancing Stage to select parents of preferably-low and strictly-same rank. The range of permitted rank values is 0 to 15. The value 63 is used to signal that the rank has not yet been set.
- Number of Children Index (NCI): 4 bits
  Used in the Parent Request Process to prioritise the list of preferred parents.
- Number of Children of Primary Tracking Node Index (NCPTNI): 4 bits
  Used in the Load Balancing Process to select the preferred new parent node.

TOTAL = 35 bits

(An observation. Bits 0 to 4 of the Slot Index are used for the index in the short frame, but since this is only sent in the heartbeat and since the heartbeat is only sent in four of the 20 slots we could reduce this field to just two bits.)

6 TESTING THE MESH INTEGRITY

6.1 Commissioning Test

Provision for a commissioning test is provided by means of an ad-hoc StatusReq message that can be sent out to all devices that are synchronised to the mesh. Each device responds by sending a Status message.

The NCU will collect the responses for a duration equal to 16 long frames in Configuration mode or 64 long frames in Active Mode, plus an additional period of 20 seconds (to allow for propagation delays of the RACH and DLCCH messages). After collecting the responses the control panel or installation engineer should check that all expected devices have responded. If any responses are missing the NCU should be triggered to send out a succession of device-addressed StatusReq messages (one per missing RBU) and check that a response is received in each case. If still no response is received then the device will be registered as not connected to the mesh.

<u>Commissioning test</u>