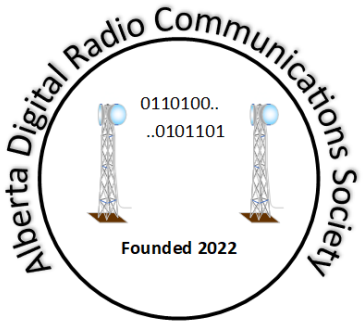

Digital Radio Projects

IP400 Node Software

Document Number: IP400-MCU
Revision: 1.3
Status: Pre-Release
Written By: Martin C. Alcock, M. Sc, MIEEE, VE6VH

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References

[1] gnu.org, "General Public Licence," [Online]. Available: https://www.gnu.org/licenses/gpl-3.0.en.html. [Accessed 25th February 2018].

[2] ST Microelectronics, "STM32WL33CC: Sub-GHz Wireless Microcontrollers.," ST Microelectronics, [Online]. Available: https://www.st.com/en/microcontrollers-microprocessors/stm32wl33cc.html. [Accessed 28 1 2025].

[3] ST Microelectronics, "Integrated Development Environment for STM32," [Online]. Available: https://www.st.com/en/development-tools/stm32cubeide.html. [Accessed 26 1 2025].

[4] ST Microelectronics, "STM32WL33 Refernce Documents," 01 02 2025. [Online]. Available: https://www.st.com/content/st_com/en/search.html#q=RM0511-t=resources-page=1. [Accessed 31 05 2025].

Revision Status

Revision	Date	Description
1.0	March 24th, 2025	Updated for phase 2 release
1.1	May 10th, 2025	Added new MAC and IP addressing
1.2	May 15th, 2025	Fixed data entry bugs and added revision numbering
1.3	May 30th, 2025	Reworked FSM, added features, reworked menus

Table 1 Revision status

Reference Documents

Author	Issue Date	Document Number	Description
M. Alcock	Jan 2025	IP400-PHY	Physical Layer Specification
M. Alcock	Mar 2025	IP400-SPI	Radio Node SPI Protocol specification
M. Alcock	Mar 2025	IP400-CC2	Nucleo-CC2 Experimenter Node

Table 2 Reference Documents

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This document is a preliminary release for a product still in development and may be subject to change in future revisions. The software described herein may be subject to unpredictable behaviour without notice. You are advised to keep a can of RAID™ Ant, Roach and Program Bug killer handy. Spray liberally on the affected area when needed.

If any page in this document is blank, it is completely unintentional.

Introduction

The IP400 project was launched to experiment with digital mesh networking on the 400 MHz band, using commercial devices designed to run in this band.

To get the project rolling, code has been developed for an STM32WL33 microcontroller [2], on several platforms that support the basic mode. Further hardware will be developed in the future for different modes.

Operation of the node is segmented into a physical layer that runs on the microcontroller, and other layers that run on different host processors. The lower layer code contains the bare minimum to send and receive frames, repeating frames and building a mesh table, and contains a simple application.

The document describes the internal application which includes a simple setup menu, and the ability to change and store station and radio parameters, as well as a simple chat application to demonstrate the capabilities. It periodically sends a ‘beacon’ frame to build the mesh tables, which contains information about the station, including latitude, longitude and grid square. Provision has also been made to connect to a GPS receiver to update the position information dynamically.

The current revision level of the firmware is the first of the phase 2 to be released.

Roadmap

Figure 1 illustrates the roadmap for the IP400 node software.

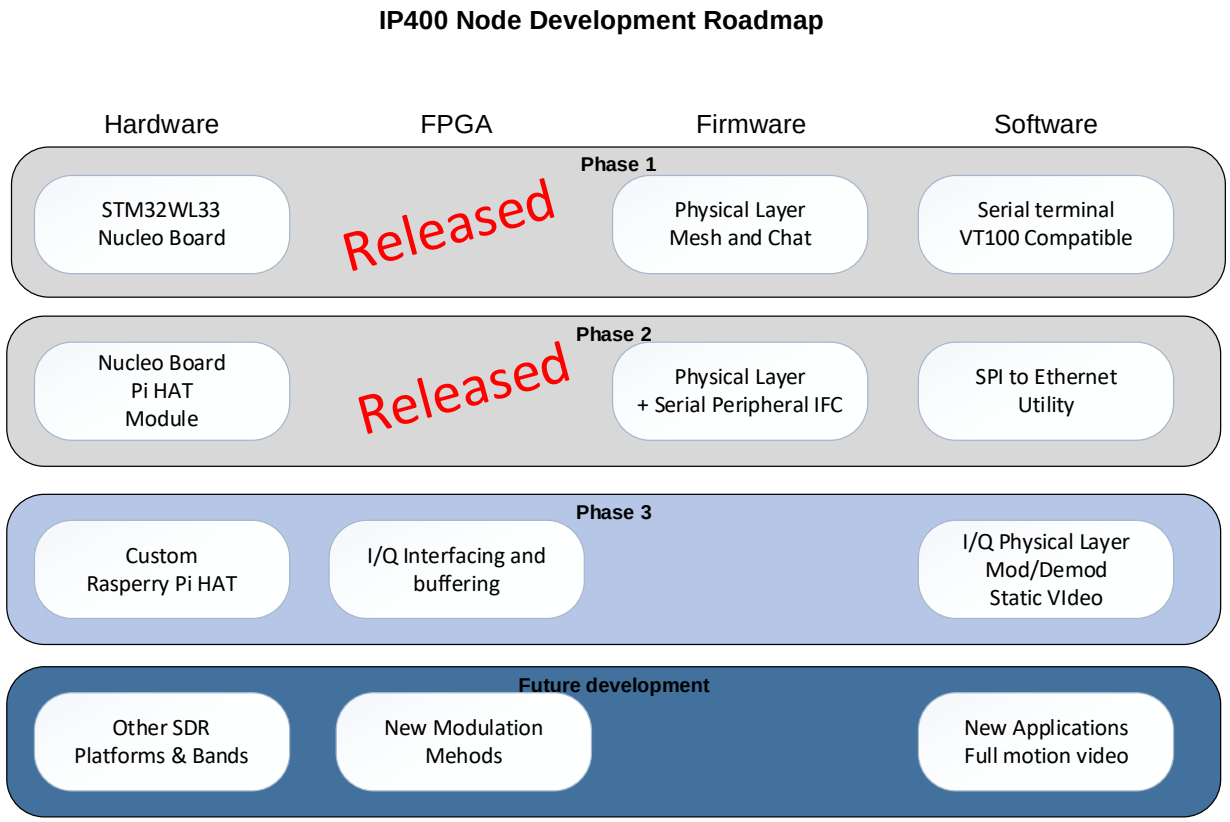

Figure 1 IP400 Node Development Roadmap

There are four phases of development for the IP400 node:

- Phase 1 is the initial evaluation phase using the Nucleo board and a simple chat application and is purely a firmware exercise. Using the PuTTY application, a connection can be made to the USART on the board. The software will implement a basic frame transmitter and receiver and be able to build a mesh table and repeat frames. The firmware can only be loaded using the ST integrated development environment (IDE) [3] and an integrated STLINK Debugger.
- Phase 2 utilizes either the Nucleo or an integrated HAT for the raspberry Pi platform. The firmware will be upgraded to include a high speed SPI, plus a downloader will be developed to alleviate the absolute requirement for the IDE, but support for an external STLINK debugger has been provided, so the IDE can also be utilized as an option. New applications on the Pi can be developed for routing, audio, file transfers, AX.25 and encapsulated IP.
- Phase 3 will introduce new custom hardware and FPGA-based signal processing for higher modulation methods and add new applications, to be determined.
- The final phase will migrate to other bands and platforms.

Main Menu

The main menu is invoked by connecting to the UAR/T on the node with a serial connection. After connecting, hit the 'X' key to invoke the menu. The main menu is shown Figure 2.

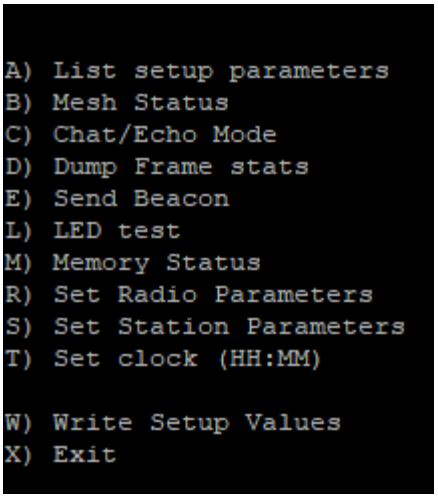

Figure 2 Main Menu

The menu items are described in Table 3.

Menu Item	Function
A	Lists the current setup parameters, including clock, station and radio
B	Displays the mesh table contents
C	Enters chat mode and echo modes
D	Dumps the frame statistics
E	Sends a beacon frame immediately
G	Dumps the NMEA sentences received from the GPS receiver[1]
L	Runs an LED test
M	Displays the memory status
R	Sets the radio parameters
S	Sets the station parameters
T	Sets the time of day clock
W	Writes the setup data to the flash
X	Repaints the menu

Table 3 Main Menu Items

Item W is used to write the setup parameters to the flash memory after modification. When powering up, if the memory is valid, the parameters are loaded. If not, then a default set of parameters is used, which can be modified accordingly.

It is possible that reloading the firmware may cause the parameters to resort to the default. This is due to changes in the setup memory layout.

[1] Only shown when compiled with GPS code enabled

Setup Parameters

A list of all the current setup parameters can be seen from the main menu item ‘A’. There are four groups of parameters:

1. Firmware version, system time, radio ID and VPN address.
2. Station callsign and description
3. Location data and capabilities
4. Radio parameters

Figure 3 illustrates them.

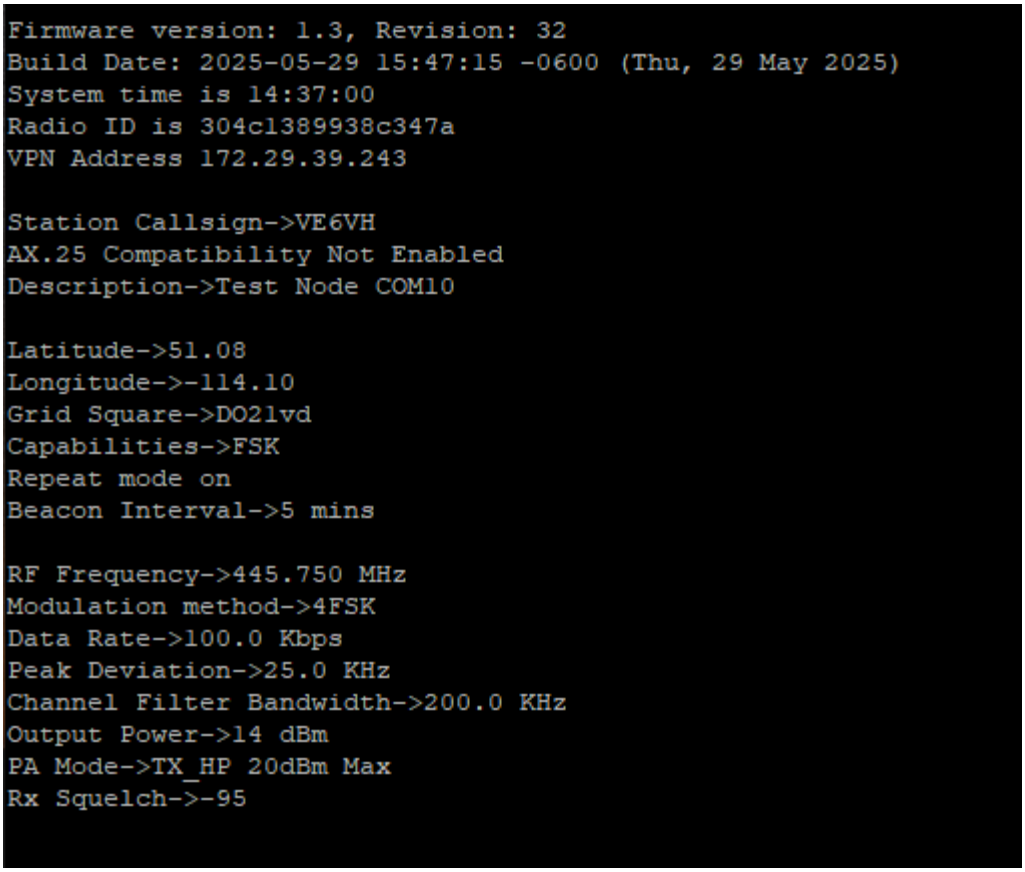

Figure 3 Setup Parameters

Mesh Table

Figure 4 illustrates the mesh table contents, and Table 4 explains them.

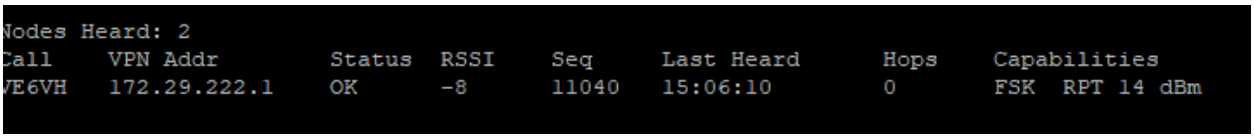

Figure 4 Mesh Table

Item	Explanation
Call	Callsign of the transmitting station. In AX.25 mode, also has the SSID
VPN Address	The network VPN address of the station
Status	OK if heard in the last hour, LOST if not.
RSSI	Receive signal strength when SYNC received (in dBm)
Next Seq	Next anticipated sequence number
Last Heard	TOD clock reading when last heard
Hops	Number of repeat hops, 0 indicates a direct signal
Capabilities	Data rate, repeat capabilities and transmitted signal strength

Table 4 Mesh Table explanation

The station capabilities can only be populated upon receipt of a beacon frame. If a non-beacon is received from a new station, it is added to the table without this field. If a beacon is heard subsequently, all the fields are updated. See Table 5 for details of these.

Bit	Capability	Meaning
0	FSK	Station can send 2 or 4 FSK
1	OFDM	Station is capable of OFDM transmissions
2	AREDN	Station is an AREDN node or has a path to one
3	REPEAT	Default setting of the repeat flag
4	EXT	Callsign is greater than 6 characters and has an extension
5	RATE	Maximum speed capability of the station[2]

Table 5 Capabilities field

[2] An explanation of these can be found in the frame layer documentation

Chat/Echo Mode

The chat mode is an interactive exchange between two nodes. Frames can be broadcast to all nodes, to all nodes with the same callsign, or to a specific node.

When invoked, it defaults to the chat mode with a broadcast address. Control keys are used to change the chat status, as shown in Table 6.

Key	Purpose
ESC	Enables entering a new destination address.
CTRL+'R'	Toggles repeat mode
CTRL+'E'	Enters echo mode
CTRL+'D'	Toggles dump mode
CTRL+'Z'	Exits chat and returns to the main menu
ENTER	Sends the current frame/ends an entry
BACKSPACE	Deletes the last character entered, or more if repeated

Table 6 Chat mode contol keys

Sending a Chat Frame

First destination address must be set, by depressing the ESC key when the cursor is at the beginning of the line, from that point there are three options:

1. Depressing the ENTER key right away will set the address to broadcast, which reaches all nodes on the network.
2. Enter a callsign and depress the ENTER key. From there one of three things can happen:
    a. If the call is not in the mesh table, it will be rejected, and the last destination will remain unchanged.
    b. If that call is unique and, in the table, then the destination will be set to the MAC address of that node. Frames will only be sent to that particular one.
    c. If that call is not unique, the destination will be set initially to all nodes with that callsign, and a list of all the entries found is displayed. Each entry has a callsign followed by a dash ('-') and an index into the mesh table.
3. Enter callsign, dash and index. If found in the table, the destination will be set to that node only.

Chat frames are displayed as follows:

- Originator callsign and VPN address
- Destination callsign and VPN address
- Number of times the frame was repeated
- Sequence number of the frame
- Data message

Dump Mode

The dump mode changes the display format to hexadecimal and also includes the frame header information. Useful for debugging.

Echo Mode

The echo mode is designed to query a node to see if it can be reached, and whether it will respond. As with the chat mode, the destination address must be set first. The CTRL/E key is multi-functional as follows:

1. The first depression enters the interactive mode.
2. The second enters a timed mode.
3. The third returns to normal chat mode.

In the interactive mode. Depressing the 'Enter' key will send a query to the remote station. The response is displayed in the current chat mode.

In the timed mode, an echo request frame is sent to the remote station approximately once every 5 seconds.

Frame Statistics

Figure 5 illustrates the frame statistics, and Table 7 explains them.

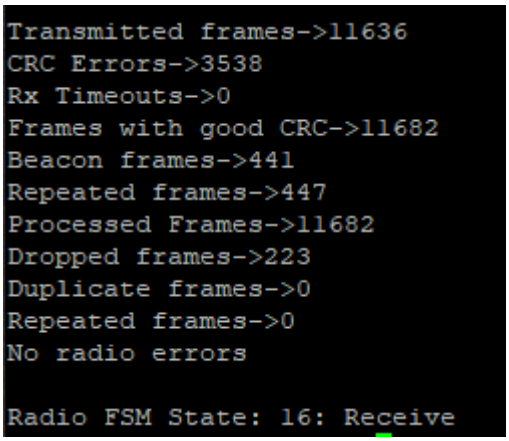

Figure 5 Frane Statistics

Item	Explanation
Transmitted Frames	The number of transmitted frames since the last restart
CRC Errors	The number of frames received with FEC errors.
Rx Timeouts	The number of times the receiver timed out
Frames Good CRC	Number of frames with a good CRC
Repeated Frames	A count of the number of frames repeated
Processed Frames	A count of the number of valid frames processed
Dropped Frames	A count of rejected frames caused by network errors
Duplicate Frames	The number of times a frame was received with the same sequence
Repeated Frames	The number of data frames repeated
Radio Errors	The last radio error encountered

Table 7 Frame statistics display

The FSM state indicates the current state of the internal state machine in the radio hardware. For a detailed explanation, see the manufacturer's reference manual. [4].

Send Beacon

This menu item sends a beacon frame immediately. The payload is a comma-delimited string, the contents are shown in

Field	Contents
Fix Source	Source of lat/long data, **FIX** for setup data, **GPS** from a receiver
Latitude	Current Latitude if GPS is connected, else supplied data.
Longitude	Current Longitude, same as above
Speed	Speed if in motion, null field if in FIX mode
Time	System or GPS time
Grid Square	Grid square from setup data
Description	System description from the setup data

Table 8Beacon Frame Payload

LED Test

The LED test will cycle through the patterns shown in the following table:

Test	Nucleo Board	PI HAT
1	RED Led	Bi Color Red
2	GREEN Led	Bi Color Green
3	All off	All off
4	Blue On	Tx LED On
5	All off	Tx LED Off

Table 9 LED Test Cycling

GPS Echo Mode

The NMEA sentences from the GPS receiver are dumped to the screen as shown below:

```
GNVTG,160.14,T,,M,0.23,N,0.42,K,A*
GNGGA,040907.000,5108.6054,N,11410.5759,W,1,07,1.53,1275.4,M,-17.5,M,,*
GLGSA,A,3,86,85,71,,,,,,,,,,1.83,1.53,0.99*
GPGSV,4,1,14,18,73,294,36,29,50,156,22,23,42,220,26,15,40,130,29*
GPGSV,4,3,14,27,07,315,,20,05,057,,10,03,225,16,07,02,007,15*
GLGSV,3,1,11,86,75,007,33,70,53,059,,71,50,151,26,87,34,305,18*
GLGSV,3,2,11,85,32,101,22,77,21,285,,78,14,344,,72,09,183,*
GNRMC,040907.000,A,5108.6054,N,11410.5759,W,0.20,160.14,070225,,,A*
GPGSA,A,3,13,18,29,05,15,,,,,,,,1.74,1.42,0.99*
GNRMC,040903.000,A,5108.6057,N,11410.5757,W,0.35,160.14,070225,,,A*
GNVTG,160.14,T,,M,0.35,N,0.65,K,A*
GLGSA,A,3,86,85,71,,,,,,,,,,1.83,1.53,0.99*
GPGSV,4,1,14,18,73,294,36,29,50,156,22,23,42,220,26,15,40,130,29*
GPGSV,4,4,14,30,01,038,,45,,,*
GLGSV,3,1,11,86,75,007,33,70,53,059,,71,50,151,26,87,34,305,18*
GLGSV,3,3,11,76,07,243,,68,04,020,,69,01,019,*
GNRMC,040907.000,A,5108.6054,N,11410.5759,W,0.20,160.14,070225,,,A*
GPGSA,A,3,18,29,05,15,,,,,,,,,1.90,1.62,1.00*
GNRMC,040908.000,A,5108.6053,N,11410.5759,W,0.26,160.14,070225,,,A*
GNVTG,160.14,T,,M,0.20,N,0.36,K,A*
GLGSA,A,3,86,85,71,,,,,,,,,,1.74,1.42,0.99*
GNVTG,160.14,T,,M,0.35,N,0.65,K,A*
```

Figure 6 GPS NMEA sentences

While this mode is active, two keys are processed:

1. Pressing the ‘ESC’ key will pause and prompt for the enter key to be hit before returning to the main menu. The data remains on the screen.
2. Pressing the ENTER key will clear the screen and return to the main menu.

Setting the clock

The time of day is entered as HH: MM. The clock has a granularity of 10 seconds and uses 24 hour format, and knows nothing about time zones, as it considers you are in your home zone.

Changing the Setup Parameters

Radio Setup Menu

To radio setup menu can be invoked from menu item 'R'. The menu is illustrated in Figure 7.

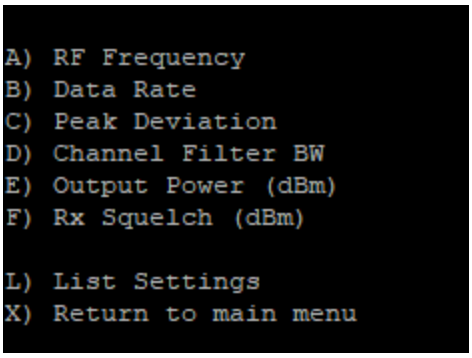

Figure 7 Radio Setup Menu

The radio setup menu items are listed in Table 10.

Item	Purpose	Format
RF Frequency	RF operating frequency from 420 to 450 MHz	XXX.XXX or NNNNNNNNN
Data Rate	Data rate 1.2 to 600Kb/s	xx.xx KHz or NNNNNN
Peak Deviation	Peak FM deviation	xx.xx KHz or NNNNNN
Channel Filter BW	BW of the receiver (See Table 11)	xx.xx KHz or NNNNNN
Output power	Sets the transmitter power	0 to +20 dBm
Rx Squelch	Sets the receiver threshold	-30 to -130 dBm

Table 10 Setup parameters

Items are changed by invoking the relevant menu item, the 'L' key lists the current settings. The bandwidth values must be one of those listed in Table 11.

Permissible Bandwidth values (KHz)							
1600	666	266	100	41.6	16.6	6.1	2.6
1510	622	244	94.4	38.9	15.3	5.9	2.4
1422	577	222	88.9	36.1	13.9	5.5	2.2
1332	533	200	83.3	33.3	12.5	5.2	2.1
1244	488	188	77.8	30.5	11.8	4.8	1.9
1154	444	178	72.2	27.8	11.1	4.5	1.7
1066	400	166	66.7	25.0	10.4	4.1	2.6
976	377	155	61.1	23.6	9.7	3.8	
888	355	144	55.6	22.2	9.0	3.5	
800	333	133	50.0	20.8	8.3	3.1	
755	311	122	47.2	19.4	7.6	2.9	
711	288	111	44.4	18.1	6.9	2.7	

Table 11 Permissible Bandwidth Values (KHz)

Station Setup Menu

The station setup menu is invoked from the main menu item 'S'. The menu is illustrated in Figure 8.

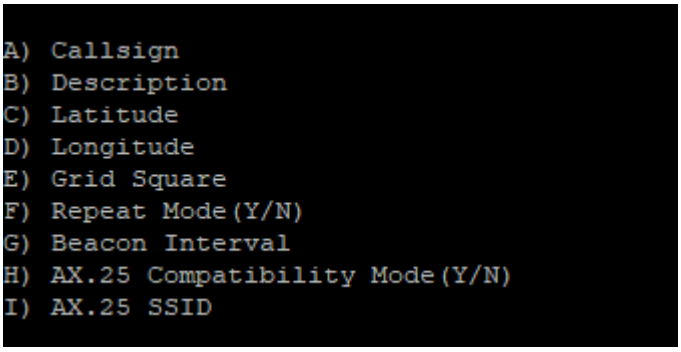

Figure 8 Station Setup Menu

Item	Purpose	Format
Callsign	Station callsign	Up to 6 characters[3]
Description	A description of the station	Up to 32 characters
Latitude	Latitude, positive for N, negative for S	±xxx.xxx[4]
Longitude	Longitude, positive for E, negative for W	±xxx.xxx
Grid Square	Home grid square	XXNNxx
Repeat Mode	Set the repeat flag in sent frames	Y or N
Beacon Interval	Interval between beacons, normally 5 mins	xx minutes
AX.25 Compatibility	Enables the AX.25 addressing mode	Y or N
AX.25 SSID	The AX.25 SSID value	0 to 15

Table 12 Station setup parameters

Note that any of these setting are not permanent until written to flash from the main menu.

[3] An extended method has been designed but not yet implemented
[4] Used in beacon frames, unless a GPS receiver is connected

Firmware Release Notes

V1.0

New Features:

1. An experimental method of generating IP addresses has been added to mesh table.
2. Frames that are repeated now have a hop table that describes the routing methods.
3. SPI communication to host a processor has been added, details are available in a separate SPI specification document.
4. New code for the Pi to exchange data between the SPI and an ethernet port.
5. Wireshark dissector for packet examination using the generic dissector.
6. Allowances have been made for a local control packet to be utilized to change parameters such as frequency, bandwidth, etc, but not fully implemented.

Changes:

1. The previous scheme of using a port number in the callsign (MAC) address field was dropped, to be reconsidered in the future for multiple nodes. Callsigns are still compressed, the other bytes can be used for additional nodes under the same callsign, up to 4 bytes.
2. Packets are now processed based on their coding types. Further information is available in the SPI protocol specification document.
3. A message is sent to the GPS receiver, when enabled, to limit the type and frequency of message to reduce the overall traffic load.

Bugs Fixed:

1. A memory leak in the queuing code has been investigated and fixed.

V1.1

The major changes in this version are to address the same callsign on more than one node. A destination address can be one of the following:

1. Broadcast: All six bytes contain 'FF' in hex. Addresses all nodes that receive it.
2. Broadcast to all of the same callsign: compressed call sign + 'FFFF' in the unique ID feild.
3. Individual address: compressed callsign + unique ID.

New Features:

1. The scheme in previous revision for IP addressing has been fully adopted.
2. New MAC addressing scheme was introduced: compressed callsign + unique ID.
3. Support for reuse of the same callsign in more than one unit has been added.
4. Chat mode was revised only to pick from the mesh table. Destination callsign selection logic has been revamped.

Changes:

1. Changed the conditional compilation for the second UAR/T to make it more generic for other purposes.
2. Created new IDE projects for the Pi HAT variants.
3. Added new hardware types in config.h, these are unique to each project.
4. Removed duplicate code in frame.h for sending frames, merged into one function.
5. Corrected LED test console output for Nucleo board.
6. Added ageing out of stations in the mesh table. After 30 minutes it goes into a 'lost' status, if heard again it will recover. After 60 minutes it is removed from the table.
7. Editing was applied to entries for the parameters to ensure correct case and format. Callsigns, for example are shifted to upper case if entered in lower.

V1.2

New Features:
To clear up any future confusion, the 'A' item on the menu now includes revision and build information Firmware version: 1.2, Revision: nn Build Date: YYYY-MM-DD. The Revision matches a commit to the development repo, and the build date is the date and time of build, offset to Zulu time, and an interpreted date.

Bugs Fixed:

1. A bug was discovered in the setup for the beacon setting, which was overwriting the station capabilities. This bug has been rectified and limits on data entry have been added.
2. The backspace processing was also determined to not operate properly if it went back to the beginning of the line. This has also been fixed. The field validator now prints an error message if the validation fails.

V1.3

Bugs Fixed:
A bug was found that caused the transmitter to hang occasionally. The radio state machine was removed from its current source location and moved to a new file, and double buffering was added to increase overall throughput.

New Features:

1. Two new frame types; an echo request and response, were added and an echo mode (aka ping) was added to the chat mode. Depressing CTRL/E once enters into an ‘on demand’ echo mode, a second time sends it every 5 seconds. CTRL/E again will cancel it. A destination address has to be set first to use it, broadcast is not permitted.
2. The previous scheme of ‘IP’ addresses has been renamed to ‘VPN’, which more closely reflects what it is. No functional changes were introduced.

3. An AX.25 compatibility mode has been added, to enable backwards compatibility with older systems. This mode has to be enabled in the station menu.
4. A description field has been added to the setup menu, which is sent in beacon frames. The field can contain up to 32 characters.