

Arduino LoRaWAN MAC in C (LMIC)

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LMIC Product Information

The LMIC library was originally developed and marketed by the IBM Zurich Research Laboratory (IBM Research GmbH), 8803 Rüschlikon, Switzerland. For additional information please contact: lpsc@zurich.ibm.com. This document was taken from V1.6, from July 2016.

The library was adapted for Arduino by Mathijs Kooijman and Thomas Telkamp. This version of the document describes the version being maintained by MCCI Corporation at <https://github.com/mcci-catena/arduino-lmic/>.

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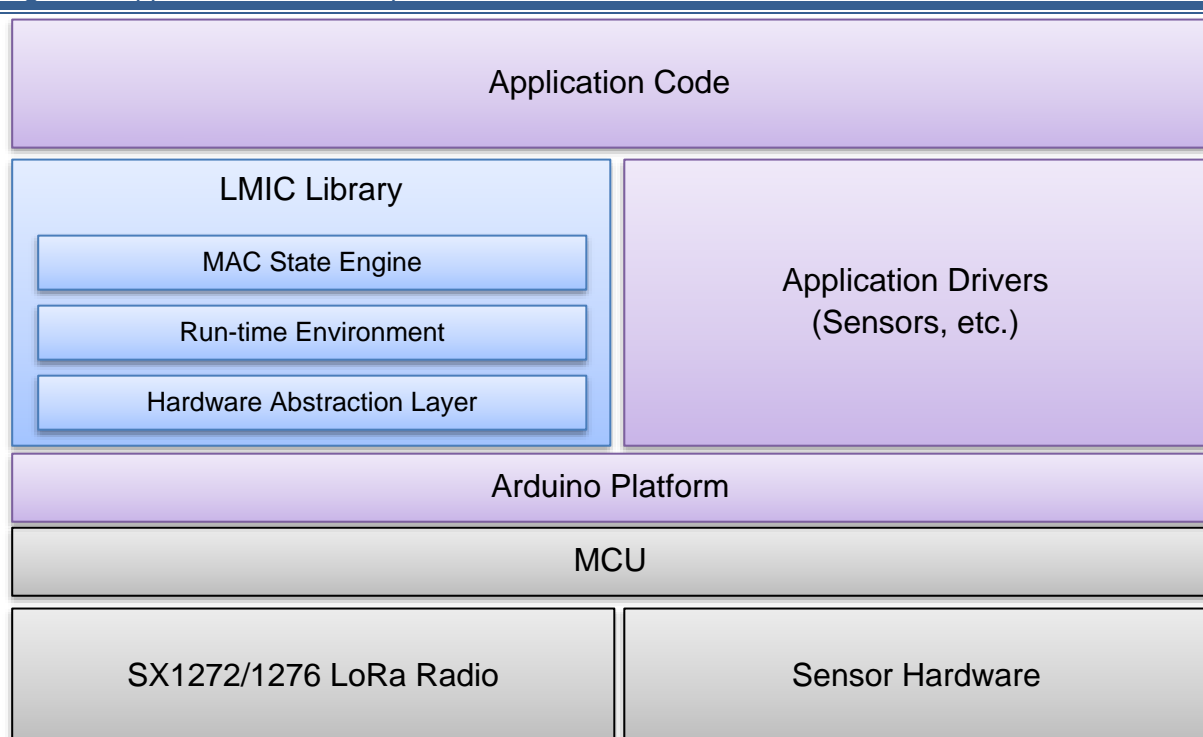
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1. Introduction

The Arduino IBM LoRaWAN C-library (LMIC) is a portable implementation of the LoRaWAN™ 1.0.2 end-device specification in the C programming language. (“LMIC” stands for “LoRaWAN MAC in C”). It supports the EU-868, US-915, AU-921, AS-923 and IN-866 variants of the specification and it can handle class A and class B devices. The library takes care of all logical MAC states and timing constraints and drives the SEMTECH SX1272 or SX1276 radio. This way, applications are free to perform other tasks and the protocol compliance is guaranteed by the library. In order to ensure compliance with the specification and associated regulations, the state engine has been tested and verified using a logic simulation environment. The library has been carefully engineered to precisely satisfy the timing constraints of the MAC protocol and to even consider possible clock drifts in the timing computations. Applications can access and configure all functionality via a simple event-based programming model and do not have to deal with platform-specific details like interrupt handlers. By using a thin hardware abstraction layer (HAL), the library can be easily ported to new hardware platforms. An Arduino HAL is provided which allows for easy integration with most Arduino variants. Eight-bit AVR platforms are supported as well as 32-bit platforms.

In addition to the provided LMIC library, a real-world application also needs drivers for the sensors or other hardware it desires to control. These application drivers are outside the scope of this document and is not part of this library.

Figure 1. Application device components



High-level view of all application device components.

1.1 LoRaWAN Versions and Features Supported

The LMIC library supports the LoRaWAN specification V1.0.2. It is also believed to support V1.0.3. It does not support V1.1.

Class B support with V1.0.2 in the US and V1.0.3 networks is not tested.

LoRaWAN 1.0.3 Class B multicast downlinks are not supported.

Class C operation is not supported.

1.2 Class A and Class B Support

The Arduino LMIC library can be configured to support LoRaWAN Class A and Class B operation. A Class A device receives only at fixed times after transmitting a message. This allows for low power operation, but means that downlink latency is controlled by how often the device transmits. A Class B device synchronizes to beacons transmitted by the network, and listens for messages at certain intervals (“ping slots”) during the interval between beacons.

Devices (and the LMIC library) start out as Class A devices, and switch to Class B based on requests from the application layer of the device.

This document uses the term “pinging” to mean that the LMIC is operating in Class B and also listening for downlink during ping slots. If a device is pinging, then the LMIC must also be tracking the beacon. It is possible to track the beacon (perhaps for time synchronization purposes) without enabling pinging.

Since many devices and networks only support Class A operation, the library can be configured at compile time to omit support for tracking and pinging. It is possible to omit support for pinging without omitting support for tracking.

2. Programming Model and API

The LMIC library can be accessed via a set of API functions, run-time functions, callback functions, and a global LMIC data structure. The interface is defined in a single header file “`lmic.h`” which all applications should include.

```
#include "lmic.h"
```

The library version follows Semantic Versioning 2.0.0 (<https://semver.org/>). A single symbol represents the version. Bits 31..24 represent the major version, bits 23..15 the minor version, and bits 15..8 represent the patch. Bits 7..0 are used for representing local changes such as pre-release or build number.

A function-like macro, `ARDUINO_LMIC_VERSION_CALC()`, is used to construct version numbers.

```
#define ARDUINO_LMIC_VERSION ARDUINO_LMIC_VERSION_CALC(2, 2, 2, 0)
```

For convenience, the library supplies function-like macros `ARDUINO_LMIC_VERSION_GET_MAJOR()`, `ARDUINO_LMIC_VERSION_GET_MINOR()`, `ARDUINO_LMIC_VERSION_GET_PATCH()`, and `ARDUINO_LMIC_VERSION_GET_LOCAL()`, which extract the appropriate field from a version number.

To identify the original version of the IBM LMIC library two constants are defined in this header file.

```
#define LMIC_VERSION_MAJOR 1  
#define LMIC_VERSION_MINOR 6
```

These version strings identify the base version of the library, and will not change.

2.1 Programming Model

The LMIC library offers a simple event-based programming model where all protocol events are dispatched to the application’s `onEvent()` callback function (see 2.3.4). In order to free the application of details like timings or interrupts, the library has a built-in run-time environment to take care of timer queues and job management.

2.1.1 Application jobs

In this model all application code is run in so-called jobs which are executed on the main thread by the run-time scheduler function `os_runloop()` (see 2.2.6). These application jobs are coded as normal C functions and can be managed using the run-time functions described in section 2.1.3. For the job management an additional per job control struct `osjob_t` is required which identifies the job and stores context information. **Jobs must not be long-running** in order to ensure seamless operation! They should only update state and schedule actions, which will trigger new job or event callbacks.

2.1.2 Main event loop

All an application must do is to initialize the run-time environment using the `os_init()` or `os_init_ex()` function and then periodically call the job scheduler function `os_runloop_once()`. In

order to bootstrap protocol actions and generate events, an initial job needs to be set up. Therefore, a startup job is scheduled using the `os_setCallback()` function.

```
osjob_t initjob;

void setup () {
    // initialize run-time env
    os_init();
    // setup initial job
    os_setCallback(&initjob, initfunc);
}

void loop () {
    // execute scheduled jobs and events
    os_runloop_once();
}
```

The startup code shown in the `initfunc()` function below initializes the MAC and starts joining the network.

```
// initial job
static void initfunc (osjob_t* j) {
    // reset MAC state
    LMIC_reset();
    // start joining
    LMIC_startJoining();
    // init done - onEvent() callback will be invoked...
}
```

The `initfunc()` function will return immediately, and the `onEvent()` callback function will be invoked by the scheduler later on for the events `EV_JOINING`, `EV_JOINED` or `EV_JOIN_FAILED`.

2.1.3 OS time

The LMIC uses values of the type `ostime_t` to represent time in ticks. The rate of these ticks defaults to 32768 ticks per second, but may be configured at compile time to any value between 10000 ticks per second and 64516 ticks per second.

In general, one tick is not an integral number of microseconds or milliseconds. Convenience functions are provided for switching back and forth.

```
typedef int32_t ostime_t;
```

Note that this is a *signed integer* value; care must be taken when computing differences to avoid being fooled by overflow. OS time starts at zero, and increments uniformly to `INT32_MAX`; it then wraps to `INT32_MIN` and increments uniformly up to zero, and repeats. Rather than comparing two `ostime_t` values, recommended practice is to subtract them and see if the result is positive or negative.

2.2 Run-time Functions

The run-time functions mentioned before are used to control the run-time environment. This includes initialization, scheduling and execution of the run-time jobs.

2.2.1 void `os_init` ()

Initialize the operating system by calling `os_init_ex(NULL)`.

2.2.2 void `os_init_ex` (const void * `pHalData`)

To facilitate use of this library on multiple platforms, the `os_init_ex()` routine takes an arbitrary pointer to platform data. The Arduino LMIC default HAL implementation expects this pointer to be a reference to a C++ struct `lmic_pinmap` object. See `README.md` for more information.

2.2.3 void `os_setCallback` (`osjob_t*` `job`, `osjobcb_t` `cb`)

Prepare an immediately runnable job. This function can be called at any time, including from interrupt handler contexts (e.g. if a new sensor value has become available).

2.2.4 void `os_setTimedCallback` (`osjob_t*` `job`, `ostime_t` `time`, `osjobcb_t` `cb`)

Schedule a timed job to run at the given timestamp (absolute system time). This function can be called at any time, including from interrupt handler contexts.

2.2.5 void `os_clearCallback` (`osjob_t*` `job`)

Cancel a run-time job. A previously scheduled run-time job is removed from timer and run queues. The job is identified by the address of the job struct. The function has no effect if the specified job is not yet scheduled.

2.2.6 void `os_runloop` ()

Execute run-time jobs from the timer and from the run queues. This function is the main action dispatcher. It does not return and must be run on the main thread. This routine is normally not used in Arduino environments, as it disables the normal calling of the `Arduino loop()` function.

2.2.7 void `os_runloop_once` ()

Execute run-time jobs from the timer and from the run queues. This function is just like `os_runloop()`, except that it returns after dispatching the first available job.

2.2.8 `ostime_t` `os_getTime` ()

Query absolute system time (in ticks).

2.2.9 `ostime_t` `us2osticks`(`s4_t` `us`)

Returns the ticks corresponding to the integer value `us`. This may be a function-like macro, so `us` may be evaluated more than once. Any fractional part of the calculation is discarded.

2.2.10 `ostime_t` `us2osticksCeil`(`s4_t` `us`)

Returns the ticks corresponding to the integer value `us`. This may be a function-like macro, so `us` may be evaluated more than once. If the fractional part of the calculation is non-zero, the result is increased towards positive infinity.

2.2.11 `ostime_t us2osticksRound(s4_t us)`

Returns the ticks corresponding to the integer value `us`. This may be a function-like macro, so `us` may be evaluated more than once. The result is rounded to the nearest tick.

2.2.12 `ostime_t ms2osticks(s4_t ms)`

Returns the ticks corresponding to the integer millisecond value `ms`. This may be a function-like macro, so `ms` may be evaluated more than once. If the fractional part of the calculation is non-zero, the result is increased towards positive infinity.

2.2.13 `ostime_t ms2osticksCeil(s4_t ms)`

Returns the ticks corresponding to the integer millisecond value `ms`. This may be a function-like macro, so `ms` may be evaluated more than once.

2.2.14 `ostime_t ms2osticksRound(s4_t ms)`

Returns the ticks corresponding to the integer millisecond value `ms`. This may be a function-like macro, so `ms` may be evaluated more than once. The result is rounded to the nearest tick.

2.2.15 `ostime_t us2osticks(s4_t sec)`

Returns the ticks corresponding to the integer second value `sec`. This may be a function-like macro, so `sec` may be evaluated more than once.

2.2.16 `S4_t osticks2ms(ostime_t os)`

Returns the milliseconds corresponding to the tick value `os`. This may be a function-like macro, so `os` may be evaluated more than once.

2.2.17 `S4_t osticks2us(ostime_t os)`

Returns the microseconds corresponding to the tick value `os`. This may be a function-like macro, so `os` may be evaluated more than once.

2.3 Application callbacks

The LMIC library requires the application to implement a few callback functions. These functions will be called by the state engine to query application-specific information and to deliver state events to the application.

2.3.1 `void os_getDevEui (u1_t* buf)`

The implementation of this callback function has to provide the device EUI and copy it to the given buffer. The device EUI is 8 bytes in length and is stored in little-endian format, that is, least-significant-byte-first (LSBF).

2.3.2 `void os_getDevKey (u1_t* buf)`

The implementation of this callback function has to provide the device-specific cryptographic application key and copy it to the given buffer. The device-specific application key is a 128-bit AES key (16 bytes in length).

2.3.3 void `os_getArtEui` (`u1_t* buf`)

The implementation of this callback function has to provide the application EUI and copy it to the given buffer. The application EUI is 8 bytes in length and is stored in little-endian format, that is, least-significant-byte-first (LSBF).

2.3.4 void `onEvent` (`ev_t ev`)

The implementation of this callback function may react on certain events and trigger new actions based on the event and the LMIC state. Typically, an implementation processes the events it is interested in and schedules further protocol actions using the LMIC API. The following events will be reported:

- **EV_JOINING**
The node has started joining the network.
- **EV_JOINED**
The node has successfully joined the network and is now ready for data exchanges.
- **EV_JOIN_FAILED**
The node could not join the network (after retrying).
- **EV_REJOIN_FAILED**
The node did not join a new network but is still connected to the old network.
- **EV_TXCOMPLETE**
The data prepared via `LMIC_setTxData()` has been sent, and the receive window for downstream data is complete. If confirmation was requested, the acknowledgement has been received. When handling this event, the code should also check for data reception. See 2.3.4.1 for details.
- **EV_RXCOMPLETE**
Class B only: a downlink has been received in a ping slot. The code should check for data reception. See 2.3.4.1 for details.
- **EV_SCAN_TIMEOUT**
After a call to `LMIC_enableTracking()` no beacon was received within the beacon interval. Tracking needs to be restarted.
- **EV_BEACON_FOUND**
After a call to `LMIC_enableTracking()` the first beacon has been received within the beacon interval.
- **EV_BEACON_TRACKED**
The next beacon has been received at the expected time.
- **EV_BEACON_MISSED**
No beacon was received at the expected time.
- **EV_LOST_TSYNC**
Beacon was missed repeatedly and time synchronization has been lost. Tracking or pinging needs to be restarted.
- **EV_RESET**
Session reset due to rollover of sequence counters. Network will be rejoined automatically to acquire new session.
- **EV_LINK_DEAD**
No confirmation has been received from the network server for an extended period of time. Transmissions are still possible but their reception is uncertain.

- **EV_LINK_ALIVE**
The link was dead, but now is alive again.
- **EV_LINK_DEAD**
No confirmation has been received from the network server for an extended period of time. Transmissions are still possible, but their reception is uncertain.
- **EV_TXSTART**
This event is reported just before telling the radio driver to start transmission.
- **EV_SCAN_FOUND**
This event is reserved for future use, and is never reported.

Details for specific events can be obtained from the global LMIC structure described in section 2.4.

2.3.4.1 Receiving Downlink Data

When EV_TXCOMPLETE or EV_RXCOMPLETE is received, the event-processing code should check for downlink data, and pass it to the application. To do this, use code like the following.

```
// Any data to be received?
if (LMIC.dataLen != 0) {
    // Data was received. Extract port number if any.
    u1_t bPort = 0;
    if (LMIC.txrxFlags & TXRX_PORT)
        bPort = LMIC.frame[LMIC.dataBeg - 1];
    // Call user-supplied function with port #, pMessage, nMessage
    receiveMessage(
        bPort, LMIC.frame + LMIC.dataBeg, LMIC.dataLen
    );
}
```

If you wish to support alerting the client for zero-length messages, slightly-more complex code must be used.

```
// Any data to be received?
if (LMIC.dataLen != 0 || LMIC.dataBeg != 0) {
    // Data was received. Extract port number if any.
    u1_t bPort = 0;
    if (LMIC.txrxFlags & TXRX_PORT)
        bPort = LMIC.frame[LMIC.dataBeg - 1];
    // Call user-supplied function with port #, pMessage, nMessage;
    // nMessage might be zero.
    receiveMessage(
        bPort, LMIC.frame + LMIC.dataBeg, LMIC.dataLen
    );
}
```

2.4 The LMIC Struct

Instead of passing numerous parameters back and forth between API and callback functions, information about the protocol state can be accessed via a global LMIC structure as shown below. All fields besides the ones explicitly mentioned below are read-only and should not be modified.

```

struct lmic_t {
    u1_t      frame[MAX_LEN_FRAME];
    u1_t      dataLen;    // 0 no data or zero length data, >0 byte count of data
    u1_t      dataBeg;    // 0 or start of data (dataBeg-1 is port)

    u1_t      txCnt;
    u1_t      txrxFlags; // transaction flags (TX-RX combo)

    u1_t      pendTxPort;
    u1_t      pendTxConf; // confirmed data
    u1_t      pendTxLen;
    u1_t      pendTxData[MAX_LEN_PAYLOAD];

    u1_t      bcnChnl;
    u1_t      bcnRxsyms;
    ostime_t  bcnRxtime;
    bcninfo_t bcninfo;    // Last received beacon info

    ...
    ...
};

```

This document does not describe the full struct in detail since most of the fields of the LMIC struct are used internally only. The most important fields to examine on reception (event EV_RXCOMPLETE or EV_TXCOMPLETE) are the txrxFlags for status information and frame[] and dataLen / dataBeg for the received application payload data. For data transmission the most important fields are pendTxData[], pendTxLen, pendTxPort and pendTxConf, which are used as input to the LMIC_setTxData() API function (see 2.5.11).

For the EV_RXCOMPLETE and EV_TXCOMPLETE events, the txrxFlags field should be evaluated. The following flags are defined:

- TXRX_ACK: confirmed UP frame was acked (mutually exclusive with TXRX_NACK)
- TXRX_NACK: confirmed UP frame was not acked (mutually exclusive with TXRX_ACK)
- TXRX_PORT: a port field is contained in the received frame at offset LMIC.dataBeg - 1.
- TXRX_DNW1: received in first DOWN slot (mutually exclusive with TXRX_DNW2)
- TXRX_DNW2: received in second DOWN slot (mutually exclusive with TXRX_DNW1)
- TXRX_PING: received in a scheduled RX slot

For the EV_TXCOMPLETE event the fields have the following values:

Received frame	LMIC.txrxFlags						LMIC.dataLen	LMIC.dataBeg
	ACK	NACK	PORT	DNW1	DNW2	PING		
nothing	0	0	0	0	0	0	0	0
empty frame	x	x	0	x	x	0	0	x
port only	x	x	1	x	x	0	0	x
port+payload	x	x	1	x	x	0	x	x

For the EV_RXCOMPLETE event the fields have the following values:

Received frame	LMIC.txrxFlags						LMIC.dataLen	LMIC.dataBeg
	ACK	NACK	PORT	DNW1	DNW2	PING		
empty frame	0	0	0	0	0	1	0	x
port only	0	0	1	0	0	1	0	x
port+payload	0	0	1	0	0	1	x	x

2.5 API Functions

The LMIC library offers a set of API functions to control the MAC state and to trigger protocol actions.

2.5.1 void `LMIC_reset` ()

Reset the MAC state. Session and pending data transfers will be discarded.

2.5.2 bit_t `LMIC_startJoining` ()

Immediately start joining the network. Will be called implicitly by other API functions if no session has been established yet. The events `EV_JOINING` and `EV_JOINED` or `EV_JOIN_FAILED` will be generated.

2.5.3 void `LMIC_tryRejoin` ()

Check if other networks are around which can be joined. The session to the current network is kept if no new network is found. The events `EV_JOINED` or `EV_REJOIN_FAILED` will be generated.

2.5.4 void `LMIC_setSession` (u4_t *netid*, devaddr_t *devaddr*, u1_t* *nwkKey*, u1_t* *artKey*)

Set static session parameters. Instead of dynamically establishing a session by joining the network, precomputed session parameters can be provided. To resume a session with precomputed parameters, the frame sequence counters (`LMIC.seqnoUp` and `LMIC.seqnoDn`) must be restored to their latest values.

2.5.5 bit_t `LMIC_setupBand` (u1_t *bandidx*, s1_t *txpow*, u2_t *txcap*)

Create new band with the specified transmit power and duty cycle (`1/txcap`) properties.

2.5.6 bit_t `LMIC_setupChannel` (u1_t *channel*, u4_t *freq*, u2_t *drmap*, s1_t *band*)

Create new channel in the given band using the specified frequency and allowing the data rates defined in the data rate bitmask (`1 << DRx`).

2.5.7 void `LMIC_disableChannel` (u1_t *channel*)

Disable specified channel.

2.5.8 void `LMIC_setAdrMode` (bit_t *enabled*)

Enable or disable data rate adaptation. Should be turned off if the device is mobile.

2.5.9 void `LMIC_setLinkCheckMode` (bit_t *enabled*)

Enable/disable link check validation. Link check mode is enabled by default and is used to periodically verify network connectivity. Must be called only if a session is established.

2.5.10 void `LMIC_setDrTxpow` (dr_t *dr*, s1_t *txpow*)

Set data rate and transmit power. Should only be used if data rate adaptation is disabled.

2.5.11 void LMIC_setTxData ()

Prepare upstream data transmission at the next possible time. It is assumed, that `pendTxData`, `pendTxLen`, `pendTxPort` and `pendTxConf` have already been set. Data of length `LMIC.pendTxLen` from the array `LMIC.pendTxData[]` will be sent to port `LMIC.pendTxPort`. If `LMIC.pendTxConf` is true, confirmation by the server will be requested. The event `EV_TXCOMPLETE` will be generated when the transaction is complete, i.e. after the data has been sent and eventual down data or a requested acknowledgement has been received.

2.5.12 int LMIC_setTxData2 (u1_t port, xref2u1_t data, u1_t dlen, u1_t confirmed)

Prepare upstream data transmission at the next possible time. Convenience function for `LMIC_setTxData()`. If `data` is NULL, the data in `LMIC.pendTxData[]` will be used.

2.5.13 void LMIC_clrTxData ()

Remove data previously prepared for upstream transmission.

2.5.14 bit_t LMIC_enableTracking (u1_t tryBcnInfo)

Enable beacon tracking. A value of 0 for `tryBcnInfo` indicates to start scanning for the beacon immediately. A non-zero value specifies the number of attempts to query the server for the exact beacon arrival time. The query requests will be sent within the next upstream frames (no frame will be generated). If no answer is received scanning will be started. The events `EV_BEACON_FOUND` or `EV_SCAN_TIMEOUT` will be generated for the first beacon, and the events `EV_BEACON_TRACKED`, `EV_BEACON_MISSED` or `EV_LOST_TSYNC` will be generated for subsequent beacons.

2.5.15 void LMIC_disableTracking ()

Disable beacon tracking. The beacon will be no longer tracked and, therefore, also pinging will be disabled.

2.5.16 void LMIC_setPingable (u1_t intvExp)

Enable pinging and set the downstream listen interval. Pinging will be enabled with the next upstream frame (no frame will be generated). The listen interval is 2^{intvExp} seconds, valid values for `intvExp` are 0-7. This API function requires a valid session established with the network server either via `LMIC_startJoining()` or `LMIC_setSession()` functions (see sections 2.5.2 and 2.5.4). If beacon tracking is not yet enabled, scanning will be started immediately. In order to avoid scanning, the beacon can be located more efficiently by a preceding call to `LMIC_enableTracking()` with a non-zero parameter. Additionally to the events mentioned for `LMIC_enableTracking()`, the event `EV_RXCOMPLETE` will be generated whenever downstream data has been received in a ping slot.

2.5.17 void LMIC_stopPingable ()

Stop listening for downstream data. Periodical reception is disabled, but beacons will still be tracked. In order to stop tracking, the beacon a call to `LMIC_disableTracking()` is required.

2.5.18 void LMIC_sendAlive ()

Send one empty upstream MAC frame as soon as possible. Might be used to signal liveness or to transport pending MAC options, and to open a receive window.

2.5.19 void `LMIC_shutdown` ()

Stop all MAC activity. Subsequently, the MAC needs to be reset via a call to `LMIC_reset()` and new protocol actions need to be initiated.

2.5.20 void `LMIC_requestNetworkTime` (`lmic_request_network_time_cb_t *`, void `*pUserData`)

Register a network time MAC request to be forwarded with the next uplink frame. The first argument is a pointer to a function, with the following signature.

```
typedef void LMIC_ABI_STD lmic_request_network_time_cb_t (void * pUserData, int
flagSuccess);
```

This function is called after processing is complete. `flagSuccess` will be non-zero if time was successfully obtained, zero otherwise. `pUserData` in the callback will be set according to the value of `pUserData` in the original call to `LMIC_requestNetworkTime()`. If not used, please use a NULL pointer.

2.5.21 int `LMIC_getNetworkTimeReference` (`lmic_time_reference_t *pReference`)

Fetch a time reference for the most-recently obtained network time. The `lmic_time_reference_t` structure at `pReference` is updated with the relevant information. The result of this call is a Boolean indicating whether a valid time was returned if non-zero, a valid time was returned, otherwise no valid time was available (or `pReference` was NULL). If unsuccessful, `*pReference` is not modified.

The structure `lmic_time_reference_t` has the following fields.

```
typedef struct {
    ostime_t tLocal;
    lmic_gpstime_t tNetwork;
} lmic_time_reference_t;
```

`tNetwork` is set to the GPS time transmitted by the network in the `DeviceTimeAns` message. `tLocal` is calculated, by converting the fractional part of the `DeviceTimeAns` message into OS ticks, and subtracting that from the completion time of the `DeviceTimeReq` message.

The two fields establish a relationship between a given OS time `tLocal` and a given GPS time `tNetwork`. From this, you can work out the current OS time corresponding to a given GPS time, using a formula like `ostime = ref.tLocal + sec2osticks(gpstime - ref.tNetwork)`.

3. Hardware Abstraction Layer

The LMIC library is separated into a large portion of portable code and a small platform-specific part. By implementing the functions of this hardware abstraction layer with the specified semantics, the library can be easily ported to new hardware platforms.

3.1 HAL Interface

The following groups of hardware components must be supported:

- Four digital I/O lines are needed in output mode to drive the radio's antenna switch (RX and TX), the SPI chip select (NSS), and the reset line (RST).
- Three digital I/O lines are needed in input mode to sense the radio's transmitter and receiver states (DI00, DI01 and DI02).
- A SPI unit is needed to read and write the radio's registers.
- A timer unit is needed to precisely record events and to schedule new protocol actions.
- An interrupt controller is needed to forward interrupts generated by the digital input lines.

This section describes the function interface required to access these hardware components:

3.1.1 `void hal_init ()`

Initialize the hardware abstraction layer. Configure all components (IO, SPI, TIMER, IRQ) for further use with the `hal_xxx()` functions. This function is deprecated and obsolete. The LMIC library calls `hal_init_ex()` instead. The client cannot call `hal_init()` or `hal_init_ex()` directly, as they are called from `os_init()/os_init_ex()`, and they must only be called once.

3.1.2 `void hal_init_ex (const void *pHalData)`

Initialize the hardware abstraction layer. Configure all components (IO, SPI, TIMER, IRQ) for further use with the `hal_xxx()` functions. `pHalData` is a pointer to HAL-specific data. When running with the Arduino HAL, this must be a pointer to a `lmic_pinmap` structure. The LMIC library calls `hal_init_ex()`. The client cannot call `hal_init()` or `hal_init_ex()` directly, as they are called from `os_init()/os_init_ex()`, and they must only be called once.

3.1.3 `void hal_failed ()`

Perform "fatal failure" action. This function will be called by code assertions on fatal conditions. Possible actions could be HALT or reboot.

3.1.4 `void hal_pin_rxtx (u1_t val)`

Drive the digital output pins RX and TX (0=receive, 1=transmit).

3.1.5 `void hal_pin_rst (u1_t val)`

Control the radio RST pin (0=low, 1=high, 2=floating)

3.1.6 void `radio_irq_handler` (`u1_t dio`)

When the HAL detects a rising edge on any of the three input lines DIO0, DIO1 and DIO2, it must notify the LMIC. It may do this by calling the function `radio_irq_handler()`. It must set `dio` to indicate the line which generated the interrupt (0, 1, 2). This routine is a wrapper for `radio_irq_handler_v2()`, and just calls `os_getTime()` to get the current time. If your hardware can capture the interrupt time more accurately, your HAL should use `radio_irq_handler_v2()`.

3.1.7 void `radio_irq_handler_v2` (`u1_t dio`, `os_time_t tIrq`)

When the HAL detects a rising edge on any of the three input lines DIO0, DIO1 and DIO2, it must notify the LMIC. If the HAL has a high-accuracy time-stamp for when the line changed state, it should call the function `radio_irq_handler_v2()`. Set `dio` to indicate the line which changed (0, 1, 2). Set `tIrq` to the time-stamp of when the line changed state.

3.1.8 void `hal_spi_read`(`u1_t cmd`, `u1_t* buf`, `size_t len`)

Perform a SPI read. Write the command byte `cmd`, then read `len` bytes into the buffer starting at `buf`.

3.1.9 void `hal_spi_write`(`u1_t cmd`, `const u1_t* buf`, `size_t len`)

Perform a SPI write. Write the command byte `cmd`, followed `len` bytes from buffer starting at `buf`.

3.1.10 `u4_t hal_ticks` ()

Return 32-bit system time in ticks (same units as `ostime_t`).

3.1.11 void `hal_waitUntil` (`u4_t time`)

Busy-wait until specified timestamp (in ticks) is reached.

3.1.12 `u1_t hal_checkTimer` (`u4_t targettime`)

Check and rewind timer for given `targettime`. Return 1 if `targettime` is close (not worthwhile programming the timer). Otherwise rewind timer for exact `targettime` or for full timer period and return 0. The only action required when `targettime` is reached is that the CPU wakes up from possible sleep states.

3.1.13 void `hal_disableIRQs` ()

Disable all CPU interrupts. Might be invoked nested. But will always be followed by matching call to `hal_enableIRQs()`.

3.1.14 void `hal_enableIRQs` ()

Enable CPU interrupts. When invoked nested, only the outmost invocation actually must enable the interrupts.

3.1.15 void `hal_sleep` ()

Sleep until interrupt occurs. Preferably system components can be put in low-power mode before sleep, and be re-initialized after sleep. When using the Arduino reference implementation, this is a no-op.

3.1.16 `s1_t hal_getRssiCal ()`

Get the RSSI calibration for the radio, in dB. The radio driver adds this to the indicated RSSI to convert to absolute dB, for doing listen-before-talk computations. Not used unless listen-before-talk is configured for this region.

3.1.17 `ostime_t hal_setModulePower (bool val)`

Request that the module be powered up or down. If true, TCXO power should be activated, and any normally high-Z control lines should be activated. This function returns the number of ticks of delay that must be inserted before using the radio. If module-level power control is not implemented, or if the radio is already in the desired state, this routine can just return zero. Normally a delay of a few milliseconds is needed when turning power on, but no delay is needed if power is already on or if turning power off.

3.2 HAL Reference Implementation for Arduino

The Arduino LMIC library includes a reference implementation of the HAL for the Arduino. Please refer to [README.md](#) for information about the implementation.

4. Examples

A set of examples is provided to demonstrate how typical node applications can be implemented with only a few lines of code using the LMIC library.

5. Release History

The Arduino LMIC release history is in the README.md file.

5.1 IBM Release History

Version and date	Description
V 1.0 November 2014	Initial version.
V 1.1 January 2015	Added API <code>LMIC_setSession()</code> . Minor internal fixes.
V 1.2 February 2015	Added APIs <code>LMIC_setupBand()</code> , <code>LMIC_setupChannel()</code> , <code>LMIC_disableChannel()</code> , <code>LMIC_setLinkCheckMode()</code> . Minor internal fixes.
V 1.4 March 2015	Changed API: port indicator flag in <code>LMIC.txrxFlags</code> has been inverted (now <code>TXRX_PORT</code> , previously <code>TXRX_NOPORT</code>). Internal bug fixes. Document formatting.
V 1.5 May 2015	Bug fixes and documentation update.
V 1.6 Jul 2016	Changed license to BSD. Included modem application (see <code>examples/modem</code> and <code>LMIC-Modem.pdf</code>). Added STM32 hardware drivers and Blipper board-specific peripheral code.