

# MooNet: Harnessing a Low-Power Mesh Backbone for Livestock Localisation and Monitoring

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## Abstract

Continuous monitoring of livestock health enables farmers to quickly detect and react to threats. For example, bolus sensors in the rumen stomach are widely used for cows in combination with location tracking information. Most bolus solutions use LoRa radios to transmit the sensor data and use the received signal strength for localization. However, the number of LoRa gateways needed for area coverage and localization together with their energy demands makes outdoor operation prohibitively costly. This paper examines the combination of low-power LoRa receivers with a low-power mesh network for long-term operation. In particular, it analyses the impact of different communication protocol designs on the power consumption. By synchronizing the activity schedules of sensors and mesh nodes, the proposed design achieves an average power consumption as low as 6mW, while remaining scalable to 1000 sensors. The respective significant reduction in solar panel and battery size makes it possible to economically operate such receivers outdoors.

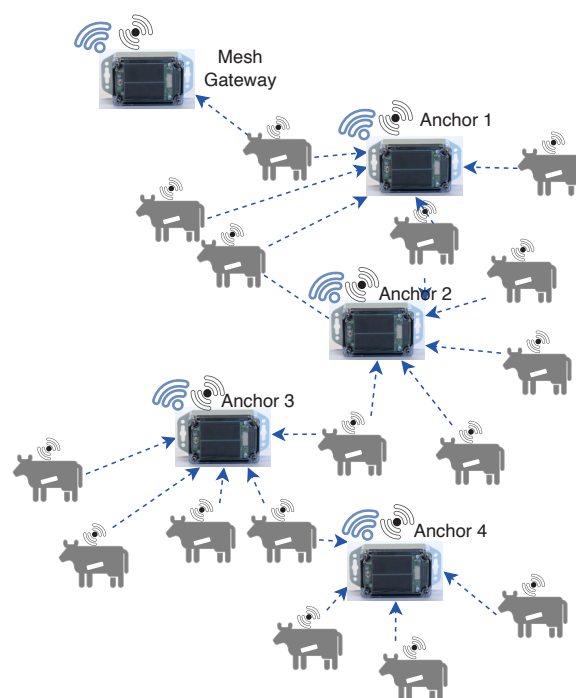
## 1 Introduction

Bolus sensors [1] inside the rumen stomach of cows enable health monitoring in order to identify and address critical health conditions early. Table 1 summarizes main features of a selection of bolus sensors available in the market. For communication, all recent systems use radios based on the Semtech LoRa modulation in the 868/915 MHz band. In order to receive the sensor data, most of the systems use full LoRaWAN gateways. Their large antennas help to cover wide areas and their software-defined receiver can decode LoRa signals without knowing the modulation parameters in advance. However, these are expensive and consume a lot of power. In contrast, the SmaXtec gateways use inexpensive LoRa radios. They compensate the reduced range by deploying more gateways and using a custom protocol with fixed modulation parameters.

Although LoRa is designed for communication beyond 10km, the attenuation caused by the cow body reduces the range to at most 500m. In practice, higher bitrates with ranges around 50–100m are used in order to reduce collisions and limit the bolus transmitter’s energy consumption. The limited range together with the gateways’ dependency on wall-power confines bolus-based health monitoring mostly to indoor operation, as installing and maintaining outdoor power cables on large farmland is expensive.

Company	SmaXtec	Moonsyst	Cattle Scan	HKT
Dimension	132x35mm	100x32mm	130x32mm	130x32mm
Range	50–100m	400m	300m	500m
Battery life	5 years	6 years	6 years	5 years
Radio	LoRa modulation @ 868/915 MHz			
Receiver	LoRa radio	LoRaWAN gateway		

**Table 1** Example Bolus Sensors in the market along with the maximum coverage and communication technology.



**Figure 1** Architecture of a solar-power mesh network with bolus inside the cows roaming in the farm in between the mesh nodes (Anchors)

Therefore, this paper examines the feasibility of battery- and solar-powered outdoor operation. Figure 1 depicts the LoRa receivers as anchors of the location tracking. Messages from a bolus are received by all nearby anchors and are then reported to the internet gateway together with the received signal strength (RSSI) and anchor position. To cover extensive farmland, long range communication to the gateway is needed, which can be accomplished with the LoRa radio of the anchors. However, forwarding all bolus messages via multiple anchors will lead to significant medium contention and will violate the airtime fairness regulations. To overcome this, we propose to use a high-

throughput, low-power mesh network based on IEEE 802.11 radios on 2.4GHz as communication backbone.

In the past, the most power-efficient solution for such mesh networks were Raspberry Pi Zero W single-board computers using the 802.11s or BATMAN mesh protocol. Their power consumption ranges from 400 to 2000mW and, for example, a solar panel of 20W peak power, i.e. a size around 40x40cm, would be a reasonable choice. However, installing and maintaining many of such large solar panels on the farmland is also expensive.

In order to significantly reduce the size of the solar panels, we combine low-power multi-radio microprocessors such as the Espressif ESP32-C6, a custom multi-hop mesh routing protocol [8,9], and clock synchronized radio duty cycling. Although the receive and transmit power consumption of the 802.11 radio is similar to single-board computers, significant energy savings are attainable by exploiting the very fast sleep and wake-up transitions. To this end, we present different communication protocol designs and analyze their impact on the average power consumption.

The analysis shows, that sleep scheduling based on synchronization across all anchors and boli allows to reduce the average power consumption of the anchor nodes down to 6mW. This makes it possible to reduce the solar panel to 200mW peak power or less, which translates into a size of just 4x3cm. In consequence, anchor node and solar panel can be combined into a weather-resistant housing that is easy to install and maintain even on extensive farmlands.

The next section summarizes related work. Section 3 describes the proposed hardware architecture and derives key power consumption parameters. Section 4 introduces the protocol designs and analyses their average power consumption based on performance modelling.

## 2 Related Work

Early research publications focused on developing wireless sensor networks for cattle health monitoring [2]. Considering the frequency selection, penetration depth and bandwidth earlier designs focused on wearable collars for the cattle. For instance, [3] used a combination of omni-directional and directional ceramic patch antennas for RF-based non-invasive sensing. Although these collars achieved a good penetration depth at 315MHz, the relationship between signal properties and cow health was inconclusive. Later, wireless communication was integrated into bolus sensors that are placed directly inside the cow's stomach [4]. These bolus sensors provide information such as body temperature, heart rate, pH level, rumination, and stress [1]. Finally, [5,6,7] provide models for the attenuation of ultra-high frequency waves through the cow body.

With the increasing availability of inexpensive long-range technologies such as Semtech's LoRa modulation and the LoRaWAN protocol, these were also adopted for bolus sensors. As visible in Table 1, many products now use LoRaWAN in the 868/915 MHz band, although the signal attenuation is worse than on the 315/433 MHz bands.

## 3 A Low-Power Mesh Backbone for Bolus Anchors

Various transceivers with support for the LoRa modulation exist and, out of these, modules with an integrated low-power microcontroller can simplify the development of the anchor nodes. One example is the RAK wireless RAK3172 module [12], which is based on the STM32WLE5CC microcontroller and has variants for all subGHz bands.

Many mesh technologies are available for the communication backbone between anchors and internet gateway. Based on the observation that the reasonable maximum distance between bolus and anchors is around 100m, the maximum distance between anchors would not be much higher. The objective of the backbone is to maximize the throughput at that distance: Higher throughput finishes transmissions faster and, hence, allows to switch back to low-power sleep earlier. IEEE 802.11, also known as Wi-Fi, achieves this by providing a wide range of bitrates and supporting large frames, e.g. 1.5kB and more, for reduced overhead.

In order to bring 802.11-based mesh networking and low-power microprocessors together, we implemented and improved the BATMAN-V protocol for the ESP32 modules family [8,9]. For power efficiency, the variants ESP32-C3, C6, and the new C5 are most interesting.

Table 2 summarizes the power consumption of different operating modes according to the manufacturer's specifications. These numbers already include the power of an idle processor. Own measurements with the Nordic Power Profiler Kit confirmed the order of magnitude. The ESP32-C6 [11] consumes around 257mW (78 mA at 3.3V) with active receiver and up to 1.3W during transmissions at maximum transmit power. Note, that typical transmissions take just 0.2–1ms even for large frames because of the high bitrates and, hence, are quite energy efficient. The RAK3172 module [12] consumes around 17mW (5.22mA at 3.3V) with active receiver.

From this we can estimate the average power consumption of an anchor node. For example, listening continuously on both radios will cost around 274mW, which is already better than the 1W baseline from a Raspberry Pi Zero mesh node. Duty cycling the 802.11 radio to 1s per minute while listening continuously on LoRa would reduce the consumption down to  $4.3+17 \approx 21$ mW.

Mode	Receive	Transmit	Processor	Sleep
Wi-Fi	257mW	1250mW	46–125mW	23–594μW
LoRa	17mW	287mW	0.7–12mW	6μW

**Table 2** Anchor power consumption with different radio operation modes based on the data sheets.

## 4 Low-Power Protocol Designs between Boli and Anchors

This section discusses and analyzes the protocol designs with focus on the communication between anchors and bolus sensors. For the mesh backbone we assume that a 1/60 duty cycle with 4mW average consumption is sufficient.

The first subsection describes the design assumptions and three protocol designs. Then, the second subsection compares their power consumption in relation to the number of bolus sensors or farm animals. The last subsection discusses the impact on the power consumption of the bolus.

#### 4.1 Protocol Designs

The protocol design must consider the following criteria:

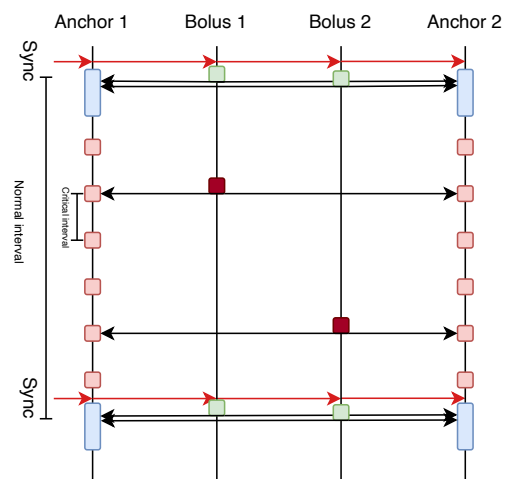
- Each bolus broadcasts a status messages every 15 minutes containing information such as bolus identifier, temperature, rumen activity indicators, pH level, and battery state. Allowable airtime for the LoRa frequency band chosen.
- If the bolus sensors indicate a critical condition, an alert message is broadcasted every 1 minute. The probability for such condition is very low, for example 5%.
- For location tracking, every anchor listens for every bolus independent of past locations, because the animal can have moved far since the last message.
- All received messages are forwarded as soon as possible to the internet gateway. We do not focus on data compression by aggregating measurements over time because this could delay the delivery of important information.

**Protocol 1** is the simplest design: The anchors listen all the time for LoRa messages from any bolus. The bolus broadcasts its messages with a random offset in order to minimize collisions. Thus, the average consumption of the anchor is 4.3mW for the mesh backbone plus 17mW for LoRa.

**Protocol 2** is inspired by the BLE periodic advertisements [14]. Every bolus starts at a randomized time but sends its messages in fixed periodic intervals. Initially, the anchors listen in order to learn the individual bolus schedules and broadcast this information to all other anchors. After all sensors are discovered, the anchors activate the LoRa receiver only shortly for potential transmissions from each bolus.

This reduces the LoRa listening time. However, each anchor still has to listen for each bolus's alert message once per minute although these are very unlikely. Because of necessary guard times around these listening intervals, the actual duty cycle of the receiver reaches 100% quickly with growing number of boli. In addition, the activity interval of two boli can overlap due to relative clock drift and, hence, result in continued message collisions.

**Protocol 3** aims to reduce the listening time for unlikely alarm messages. This is achieved by sharing a few short time slots for alarms across all boli as shown in Figure 2. Collisions in these time slots are reduced through LoRa Channel Activity Detection [13] with a small random backoff. Furthermore, an exclusive periodic time slot is assigned to each bolus for its normal status messages.



**Figure 2** Global schedule for exclusive normal status messages every 15 minutes and shared short time slots for alarm messages every minute.

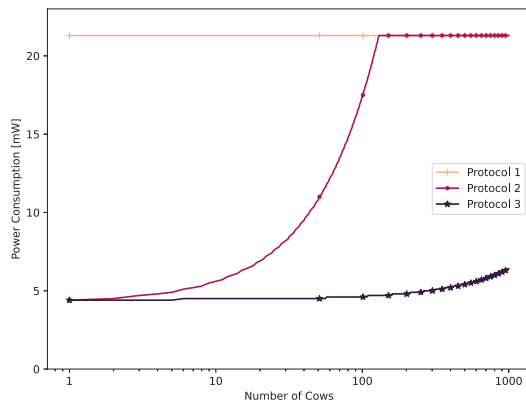
In order to establish the schedule, all anchors are first synchronized through the mesh network. Then, periodic beacon broadcasts from the anchors allow the boli to synchronize too. The shared alert time slots are also be used by the boli to request their exclusive time slot. Although much more complex, the main advantage is that a small number of alarm time slots every minute is sufficient.

#### 4.2 Protocols power consumption vs number of cows in a farm

We created a power consumption model for the anchor's LoRa radio based on the consumption values from Table 2. The power consumption of LoRa transmissions is estimated based on airtime calculations using [10] and the average number of transmissions per hour. For this, we assumed a payload size of 24bytes, 250KHz bandwidth, coding rate 4/5, and spreading factor 9.

The LoRa listening intervals are also based on the airtime calculations and include an additional guard time before and after in order to compensate for clock drift between bolus and anchor. The model does not account for overlapping listening intervals because this is not relevant for worst-case estimates.

Figure 3 shows the average power consumption depending on the number of cows from 1 to 1000. Most farms or pastures in Germany have less than 500 cows [15]. For protocol 1, the typical power consumption is 21.3mW irrespective of the number of cows. Protocol 2 has a lower power consumption of 4.4mW for a single cow. However, the consumption increases and around 130 cows it reaches protocol 1. Because of the shared alarm time slots, the consumption grows much slower for protocol 3. It reaches 6mW for 1000 cows in our model.



**Figure 3** Anchor power consumption for the three protocols and different pasture size. For readability, the horizontal axis is on a logarithmic scale.

### 4.3 Bolus Energy Budget

The bolus is inserted into the cow's rumen and stays there forever. Thus, its battery has to provide sufficient energy for the desired 5–6 years of lifetime, see Table 1. In the following we analyze only protocol 3 because it has the most activities for the bolus.

The energy consumption of sending the normal messages every 15 minutes is 0.787mWh per day based on the air-time calculator. In order to receive the beacon broadcasts from anchors, the bolus has to listen once every 15 minutes including guard times, which costs 0.209mWh per day.

The alert messages could be sent every minute but we assume that not all boli have alerts all the time. We considered pessimistically, that each bolus has 5 days of alerts in a month, which would cost in average 1.9mWh per day. This calculation also includes the listen before talk time with channel activity detection.

Thus, the estimated total energy consumption of the bolus is 2.96mWh per day. For a lifespan of 5 years, this would amount to 5.4Wh just for radio operation excluding sensors and local preprocessing. For reference, a single Li-FeS2 AA battery has a capacity of 4.5Wh (3000mAh at 1.5V) and a typical bolus has sufficient space for three of such batteries, that is 13.5Wh.

## 5 Conclusions

In this paper, we proposed a communication protocol that utilizes clock synchronization to enable low-power communication between cattle bolus sensors and nearby anchor nodes. Compared to the gateways available on the market, this can reduce the consumption from 1W to 6mW. This enables the application of solar harvesting with a small solar panel, for example with 200mW peak power and 4x3cm size. This makes it economically suitable, to install and operate a sufficient number of anchors for outdoor livestock monitoring and localization tracking.

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