Towards Energy Efficient LoRa Multihop Networks

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***Abstract*—We propose an adaptation of the well-known Time Slotted Channel Hopping (TSCH) Medium Access Control (MAC) protocol, which was initially specified for IEEE 802.15.4 based networks, for operation over the LoRa PHY layer. Thanks to its deterministic nature, multiple concurrent communications can be handled, while reducing channel collision and ensuring reliability in a power-efficient manner. The proposed solution was implemented in the Contiki-NG operating system and tested on real motes.**

***Index Terms*—LoRa, LoRa-multihop, TSCH, MAC**

I. Introduction

In the past years, different types of technologies to enable connectivity between objects and the internet, the so-called Internet of Things (IoT), have been proposed, each targeting different use cases. Amongst these technologies, Low Power Wide Area Network (LPWAN) technologies are gaining momentum, since they enable energy-efficient long range (up to several kilometers) communications, offering new possibilities for connected devices.

One of the most popular LPWAN technologies is LoRa. In Europe it uses the unlicensed 868 MHz Industrial, Scientific and Medical (ISM) band. The proprietary Chirp Spread Spectrum (CSS) modulation allows trading data throughput for range, by setting for each point to point channel two parameters, the frequency band (B) and the spreading factor (SF). For a selected B, a larger SF extends the range by improving the receiver sensitivity at the cost of data throughput. To prevent interferences, law prohibits any transmitter to use a specific channel more than 1% of the time. CSS channels with different spreading factors do not interfere.

The LoRaWAN standard proposes a star-like topology where end devices send their data to a Base Station (BS), with an ALOHA-like Medium Access Control (MAC) protocol. When the motes cannot reach the BS (no ack received on sent frame), they can decide to increase their SF. When the BS is continuously powered and connected to the Internet, LoRaWAN is a cost-effective system to collect sensor data from an area surrounding the BS. In the countryside this area can cover many km^2, but in town, with indoor sensor motes, this area is sometimes less than a km^2. Therefore, many applications require several BSs. Some telecommunications operators propose LoRaWAN BSs, connected to the Internet. These BSs often share the towers used for mobile telephony.

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The LoRaWAN-based star topology has some serious limitations as studied in [1], [2] being:

- the cost of the multiple BSs,
- batteries in motes far away from BSs need to be replaced more often,
- data packets from remote motes will have to be transmitted with the highest SF, they will occupy the channel for a long time and therefore have a high probability of collision.

These observations have motivated researchers, to investigate new networking approaches, e.g. multihop communications. Arguments in favor of exploring this approach have been extensively developed in [3]. However, multihop LoRa poses other challenges, especially at the MAC layer. Questions are: when is it the right moment to switch on the motes' radio transceiver in order to send and receive data and how to coordinate channels? In other words, how to make sure that the sender can find the receiver on the right channel at the right moment while ensuring long battery lifetime?

II. Related work

The authors of [4] designed an original MAC layer specifically for linear multihop LoRa networks, in which each node can only communicate with the preceding and following node. Such configurations occur in tunnels and pipelines. To minimize battery depletion they designed a hop by hop synchronization protocol. This protocol minimizes the time nodes have to listen before their predecessor in the line sends a message. The timings of the synchronization and the data transmission protocol take into account the statistical distribution of the frequencies of the node's clocks to set an upper limit to the probability that a node should send while the next node is asleep.

Authors of [5] developed a routing algorithm for bringing LoRA sensor data to the sink that is simpler to implement and uses less resources than the standardized Routing Protocol for Lossy networks (RPL). Their algorithm maximizes the Packet Delivery Ratio (PDR) between motes and the base station by reducing control traffic and collisions but does not attempt to minimize power consumption. It can adapt routes to changing conditions in the network. The physical parameters B and SF need to be chosen experimentally for each link. They evaluated experimentally the PDR of the resulting network and found significantly better results than those obtained with a star network.

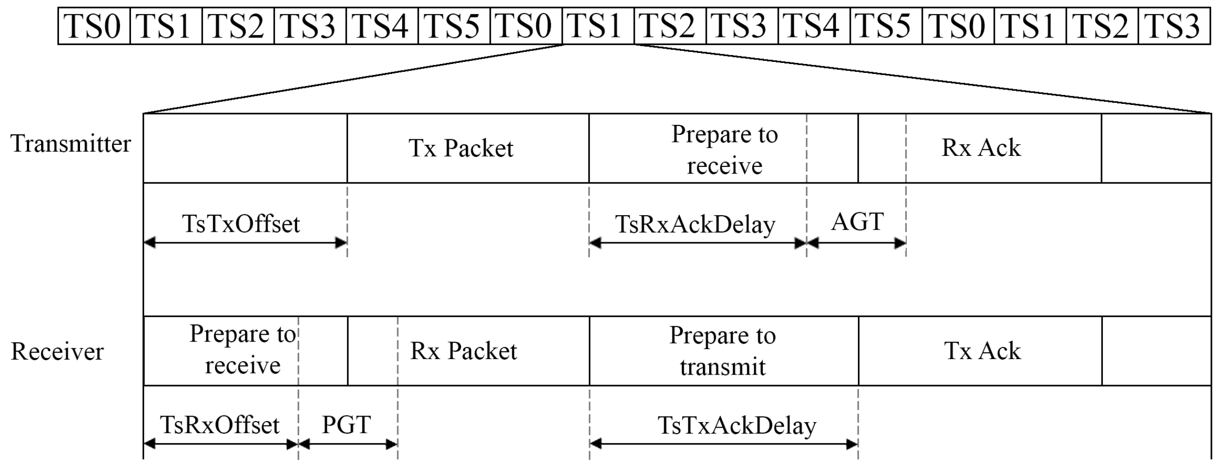

Fig. 1: TSCH slotframe and slot operation for sending and receiving data. PGT and AGT are packet and acknowledgment guardtime intervals to compensate for clock drift between motes.

In [6] the multihop LoRa network is operating on a fixed B with standard RPL, but with a new Objective Function (OF) and MAC protocol that can select SF parameters minimizing the total on-air time to reduce power consumption and interference. It has been tested on real motes and performed as expected but increased message latencies.

Authors of [7] introduce a model for estimating the power consumption of motes in a LPWAN multihop uplink network as a function of its topology. Considering that the useful lifetime of the network ends as soon as the battery of one sensor is exhausted, they conclude that star networks such as LoRaWAN and SigFox are significantly worse than networks based on the creation of concentric circles around the base station, featuring a number of motes that grows exponentially towards the outer circles. For their study on energy consumption, they assumed an ideal synchronous time slotted MAC protocol preventing collisions and power waste by receivers staying awake while waiting for messages.

III. Proposed solution

The above mentioned research work on mesh LoRa networks has mainly focused on lowering network congestion with different routing strategies, without specific mechanisms to keep duty cycle below the 1% legal restriction. In this paper we propose an adaptation on the Time- Slotted Channel-Hopping (TSCH) MAC protocol [8] for operation on the LoRa PHY layer and discuss its properties implemented in the lightweight operating system Contiki-NG [9]. The presented solution allows to use the RPL routing protocol with a fixed LoRa SF while saving energy and keeping a tight control on duty cycle.

Fig. 1 shows typical TSCH operation. Slots are grouped into slotframes (TS0 to TS5 for the slotframe depicted), that repeat over time. The timing parameters that define the actions at both transmitter and receiver side during a timeslot are shown in the figure. In order to adapt TSCH for LoRa, these timings need to be adjusted. They determine the total length of a slot. Since LoRa is much slower than IEEE 802.15.4, the length of each slot will be considerably larger for LoRa .

TsTxOffset is computed as the sum of TsTxCCAOffset, TsTxCCA and TsRxTx. These represent the offset time of the Clear Channel Assessment (CCA), the CCA processing time and the turnaround time to switch from receiving mode to transmitting [10]. LoRa performs CCA using Channel Activity Detection (CAD) [11]. TsTxOffset and TsRxOffset must be calculated so that CAD can be successful. The CAD duration is $x \cdot Tsym$, where x is a factor dependent on the spreading factor given in [12] and $Tsym = \frac{2^{SF}}{BW}$ [13]. Since our experiment was done for SF 7 and on three bands with bandwidth 125kHz, Tsym equals 1.024ms and x equals 1.92. This results in a CAD duration of 1.966 ms. TsTxOffset is found by multiplying CAD with an experimentally determined minimum value to function properly, in this case 80; $TsTxOffset = 80 \cdot CADduration = 152.830ms$. TsRxOffset is defined in Contiki-NG as TsRxOffset = TsTxOffset - PGT/2, with PGT the Packet Guard Time [9]. This guard time is introduced to compensate for clock drift between motes. The PGT (which is equal to the Acknowledgement Guard Time AGT) is not changed from its default value. TsTxAckDelay was determined the same way as TsTxOffset but with a different factor, 10 for this parameter. From it, TsRxAckDelay was derived: $TsRxAckDelay = TsTxAckDelay - \frac{PGT}{2}$ [14].

We have implemented and tested the TSCH adaptation on two Contiki-NG enabled SX1272LM1BAP Semtech LoRA motes [15], [16] that communicate using the TSCH minimal schedule and use 3 bands of 125kHz for the channel hopping with a LoRa PHY spreading factor equal to 7. The minimal schedule enables one active slot per slotframe. The timings to successfully send and receive data using TSCH over LoRa are provided in Table I.

TABLE I: TSCH for LoRa: Adapted Timings

Parameter	Meaning	Value (μs)
TsTxOffset	The time between the beginning of the timeslot and the start of frame	152830
TsRxOffset	Time delay before the receiver starts listening.	141830
Guard Time	Guard time	22000
TsTxAck-Delay	Time before sending the ACK.	19710
TsRxAck-Delay	Time delay before receiving the ACK at the sender side.	8710

With the timings provided in Table I together with the default timings, we obtained a timeslot length of 400ms. Note that this is considerably higher than for typical IEEE 802.15.4 communications at 2.4 GHz, for which the default timeslot length is 10ms.

It should be mentioned that in the current solution the overhead needed for synchronization is significant. Due to the clock drift in the SX1272LM1BAP Semtech LoRA mote a beacon is needed to resynchronize about every 1000 slots when a guard time of 22ms is used [17]. Because of the 1% duty cycle, transmission is only allowed one in 100 slots meaning that 10% of the bandwidth would be used for synchronization. A possible solution is the use of data packets for synchronization purposes. Another solution could be an increase of the guard band and finding a trade-off between the associated increase in power consumption and the decreased synchronization overhead. A careful analysis of the clock drifts in LoRa nodes and an optimization of the guard timing analog to the one developed in [10] is also a path to be explored, considering the important power savings reported.

IV. Conclusions and Future Work

In this paper, we have presented an adaptation of the TSCH MAC protocol for long range operation. This MAC mechanism allows to tackle most of the challenges that multihop LoRa communications create: the time division mechanism allows to synchronize nodes' wake ups for successful data transmission in constrained nodes, the channel hopping mechanism allows to diversify transmissions over different channels, all in a power efficient manner and keeping in mind the limitations imposed by ISM band regulations. However, in the current scope, only one SF can be selected for the whole network. Further investigation to leverage the use of multiple SFs in the same network is required.

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