Energy Efficiency Analysis of Centralized-Synchronous LoRa-based MAC Protocols

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***Abstract*—LoRa is a PHY layer technology that has been gaining popularity with IoT platfrom developers, due to its low-power long-range communication. As a result, different classes of LoRa-based MAC layer protocols have been proposed, with the key ones being either contention-based or centralized-synchronous. Since most of the research literature focused on analyzing the efficiency of contention-based LoRa protocols, we sought to study the efficiency of centralized-synchronous protocols. We utilized a tailored simulator to analyze the energy efficiency of LoRa-based centralized-synchronous protocols. Our findings, are backed up by hardware performance measurements. After comparing the energy efficiency of the centralized-synchronous protocols against that of other LoRa-based MAC layer protocol classes, we found that the lifetime of a device using a centralized-synchronous protocol was up to four times longer than that of a contention-based device. These findings, as well as our insights, will aid the development of future energy-efficient LoRa-based MAC protocols.**

***Index Terms*—IoT; LoRa; LoRaWAN; Sigfox; MAC; MoT; Media Access Protocol; ALOHA; Contention; Synchronous; Centralized.**

I. Introduction

The Internet of Things (IoT) has gained significant momentum in recent years due to the advancements in Low-Power Wide Area Networks (LPWANs) communication technologies. Such technologies offer a communication range of several kilometers while consuming minimal current, thus, enabling a multitude of possible IoT applications. LoRa, a PHY layer technology by Semtech [1], has gained significant attention in recent years. Primarily because of its low-power requirements, long-range communication coverage, and availability of modulation/demodulation hardware. Different LoRa-based MAC protocols have been proposed [2]–[5] to utilize the LoRa PHY technology. These protocols are classified as contention-based or synchronous-based.

Among LoRa-based MAC layers, LoRaWAN [2] is one protocol that has attracted the most attention from researchers, as in work done in [6]–[11]. The channel access of LoRaWAN can be described as similar to that of ALOHA [12], thus, classifying LoRaWAN as a contention-based MAC protocol.

MoT is a LoRa-based MAC protocol that was designed for mission-critical IoT applications [4]. Since mission-critical applications require minimal to zero collisions in packet transmission, a contention-based protocol would not be applicable. As a result, MoT was designed as a centralized-synchronous MAC protocol using LoRa. Although energy efficiency analysis of LoRa PHY layer has been a topic of extreme popularity in recent studies, published works have focused mostly on contention-based protocols, and minimally on the synchronous-based protocols [6], [9], [11], [13]–[15].

In this paper, we present a comprehensive analysis of the energy efficiency of LoRa-based centralized-synchronous protocols using a tailored simulator. For realistic analysis, we validate the results with hardware measurements. The results illustrate that the energy efficiency of synchronous protocols is greater than that of contention-based protocols by a range of 3-4 times. We found that an end-device using MoT, powered by a single 1000 mAh battery while sending one 10-Byte packet every 60 minutes can achieve a lifetime of up to 75 years. By comparison, a LoRaWAN end-device with the same parameters achieves a lifetime of 18 years.

The remainder of this paper is organized as follows. Section II reviews the related work. Section III models the current consumption of both classes of protocols along with a dissection of consumption sources in the LoRa PHY layer. Section IV presents our evaluation metrics and a discussion of the results. Section V, concludes our research.

II. Background

The modulation scheme that LoRa employs has enabled a more straightforward transceiver design and receiver sensitivity of up to 19.5 dB below the noise floor level [10]; these are the main reasons LoRa can provide low-power long-range communication [1]. Most of the research done on LoRa has focused on either improving or studying the energy efficiency of LoRaWAN. Meanwhile, the energy efficiency of other LoRa-based MAC layer protocols has had far less scrutiny, due to the limited research on using LoRa on MAC layer protocols other than LoRaWAN. To present our research, we first review the literature on the different LoRa-based MAC protocols, and second, we discuss two crucial LoRa-based MAC protocols LoRaWAN and MoT.

RLMAC is a LoRa-based MAC protocol designed to enable multi-hop communications [5]. The authors propose an

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objective function to be used by the RPL-routing protocol that selects the best routing path to minimize the time on air; achieved by selecting the spreading factor for each available neighbor. By reducing the time on air, the authors were able to reduce the energy consumption and therefore improve the lifetime of an RLMAC end-node.

Other researchers proposed CT-LoRa, a LoRa-based multi-hop protocol that uses synchronized packet collisions [16]. They introduce a random timing offset between packets to improve the receiver reliability. To prevent the timing offset from diverging, authors propose that the delay information be carried in each packet.

An adaptive duty-cycle MAC (ADC-MAC) protocol was proposed by authors in [17]. It uses LoRa as the PHY layer and has each node control the minimum interval of uplinks based on the residual energy, the node load, and the network congestion rate. This asynchronous protocol is shown to improve packet delivery rate and extend the node lifetime when compared to LoRaWAN [3].

For our energy-performance evaluation, we further discuss LoRaWAN as the leading contention-based class and MoT as the candidate for synchronous-based protocols.

A. LoRaWAN

LoRaWAN is a LoRa-based MAC protocol governed by the LoRa Alliance [18]. This protocol uses a star topology in which a single basestation relays all the information received from all end-devices back to a network server [19]. The channel access in LoRaWAN is based on that of ALOHA [2] causing unacceptable numbers of packet collisions.

According to the current LoRaWAN specification [12], an end-device can use one of three classes: Class A, Class B, or Class C. Each of the device classes provides a certain balance between downlink latency and power consumption.

1) Class A: This class of devices periodically transmits a packet, after which it opens up two short downlink windows. Class A devices enjoy the lowest power consumption but suffer from the highest latency. All LoRaWAN end-nodes are required to support Class A by default.

2) Class B: The Class B device is similar in operation to that of Class A, except that it has multiple scheduled downlink windows. This class of devices has moderate downlink latency and power consumption.

3) Class C: These devices have continuous receive windows to reduce the downlink latency; this, significantly increases energy consumption.

A recent study of LoRaWAN showed a significant improvement in its energy consumption compared to other LPWAN technologies [20]. However, a comparison of the energy efficiency of LoRaWAN with a synchronous protocol has to date received limited consideration in the literature.

B. MoT

MoT is a centralized, guaranteed-access wireless MAC protocol, in which a basestation coordinates and schedules multiple time-slots for the end-nodes to use for transmission. A node is scheduled to transmit only once every frame; the duration of the frame is dependent on the number of connected nodes, the payload size, and the presence of connection packets. According to [4], the latency of MoT is the duration of the frame, at a minimum of 1.7 seconds. It can be seen that from an end-node point of view, the main energy consumption aspects of the protocol rely on the duration of communication.

The advantages of MoT are its deterministic latency and guaranteed delivery of packets. MoT guarantees the delivery of all packets by acknowledging every packet without compromising duty-cycle limitations. Deterministic latency is possible due to the scheduling algorithm used, in which each node is aware of the duration of the frame as well as its scheduled time-slot.

The following sections describe and evaluate the energy consumption of LoRaWAN and MoT.

TABLE I
SYMBOLIC TIME (MS)

		Spreading Factor					
		7	**8**	**9**	**10**	**11**	**12**
	125	1.02	2.05	4.10	8.19	16.38	31.77
BW	**250**	0.51	1.02	2.05	4.10	8.19	16.38
	500	0.26	0.51	1.02	2.05	4.10	8.19

III. LoRa Energy Consumption Characteristics

The modulation complexity of LoRa is superior to any rival modulation schemes [1]; this results in a low-power radio device without compromising the link budget. Aside from having reduced complexity, a LoRa transceiver has different states of operation, each one consuming different levels of electric current. In a typical application, the key states in a LoRa PHY layer are transmission, reception, idle, and sleep. The current drain in the transmission state is dependent on the transmission power, which ranges from 22 mA to 125 mA [21], whereas the reception, idle, and sleep states consume 10.8 mA, 1.5 uA, and 0.2 uA respectively. The MAC layer controls when the device transitions from one state to the next. The time in which a LoRa device remains in either the transmission or reception state is subject to the modulation parameters. The payload is modulated into a number of symbols based on the different modulation parameters [7]. Table I lists the different symbolic times using different combinations of Spreading Frequency (SF) and Bandwidth (BW).

In the following subsections, we utilize the difference in MAC operation patterns to identify and analyze both candidate protocols for energy-performance evaluation.

A. LoRaWAN

Several studies have discussed the energy consumption of a LoRaWAN network by examining the consumption pattern in each of the three Classes [6], [8], [9], [11], [15]. When configured as Class A, the consumption pattern is transmission, idle1, reception, idle2, reception, and sleep, in which the

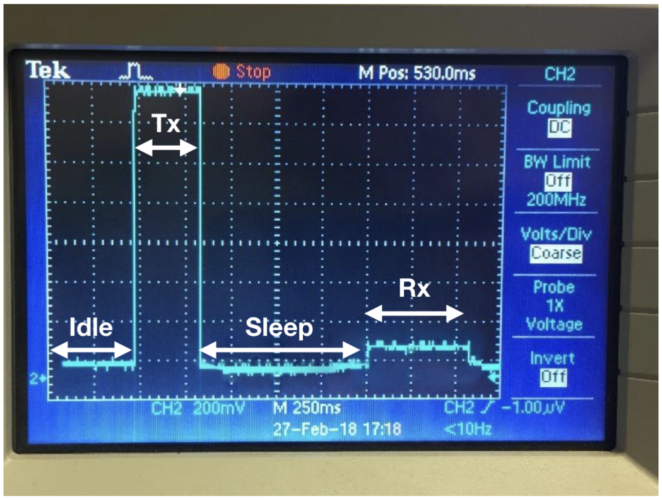

Fig. 1. Measured MoT Frame (Time values were modified for illustration purposes).

idle time is 1 and 2 seconds respectively based on the recommendation of the LoRaWAN specification [12]. However, the second downlink window (idle and receive) is not necessary if the Class A device receives a downlink message in the first downlink window. This consumption pattern suggests that the majority of the energy will be consumed during the idle and sleep times, rendering LoRaWAN inefficient for guaranteed transmissions.

B. MoT

MoT's consumption pattern is divided into idle, transmission, sleep, reception, and sleep. The idle state in MoT is mainly used for sensor initialization/activation [4]. When compared to LoRaWAN, there are two differences in MoT's operation pattern: the removal of the second downlink window, and the transition into sleep rather than idle between transmission and reception. These differences may result in reduced energy consumption of MoT compared to LoRaWAN. To our knowledge, MoT energy consumption has yet to be analyzed by researchers. However, it can be presumed from the consumption pattern of MoT, that an end-device will spend the majority of its lifetime in the sleep state.

IV. Evaluation and Results

To analyze the energy consumption of MoT as a centralized-synchronous protocol, we first validated the documented current drain in each state of the transceiver using a hardware experiment. Subsequently, we performed multiple simulations to evaluate the energy efficiency of MoT and to predict the battery life in a device using a centralized-synchronous protocol.

A. Hardware Platform

We used the Velapulsar sensing platform [22] as our testbed for evaluating MoT. The Velapulsar sensing platform uses an MSP432 [23] microcontroller, an RFM95 module as a LoRa transceiver [24], as well as different sensors. Table II

TABLE II
Current Consumption of Velapulsar [22]–[24]

State	Current Consumption
Sleep	830 nA
Idle	1281.6 nA
Transmit (14 dBm)	45.28 mA
Transmit (20 dBm)	126.28 mA
Receive	14.28 mA

illustrates the documented current consumption of Velapulsar's five operation states. To validate the current drain in each state, we connected a low-ohm high-precision 10 Ω resistor in series with Velapulsar. The resistor had to induce a voltage drop significant enough to differentiate between the various states, without significantly impacting the operating voltage of the node. We were then able to calculate the circuit-current consumption by measuring the voltage drop across the resistor using Ohms Law. Fig. 1 shows a single node cycle with idle, transmit, receive, and sleep measured by an oscilloscope. The timing for each state has been modified for illustration purposes by changing the packet size, BW and SF.

B. Simulation Environment

We adopted SimPy [25], a discrete-event simulator in Python, to build a generic LoRa network simulator. This simulator inherited many of the features of LoRaSim [26], a SimPy-based LoRa simulator that analyzes scalability by simulating packet collisions. We took LoRaSim several steps further to simulate energy consumption under predetermined parameters; these are what defines the class of MAC protocol used in the LoRa network. Table III lists the parameter values we used in order to simulate LoRaWAN and MoT. These parameters are detailed below:

• *Duty-cycle* is defined as the percentage of time a node can occupy a certain channel over a set interval. We used this parameter to set a minimum duration in which a node had to wait before sending the next packet. Due to the restrictions set by the ETSI Standard EN 300 220 V2.4.1 [27] in the bands specified in the ERC Recommendation 70-03 [28], a device can only transmit on a single channel for 1% of a set time. Accordingly, we set the duty-cycle of both protocols to 1%.

• *Number of Channels* is defined as the number of simultaneous packets a base station can receive on different frequency channels at the same time. We used this parameter to populate the channels that end-nodes can use for transmission.

• *Data Rate* is defined as the number of transmitted bits per second calculated from a combination of BW and SF. A LoRa base station can decode multiple packets received on the same frequency channel at the same time, assuming that each uses a different data rate [6]. We used this parameter to either set a fixed or an adaptive BW and SF.

• *Transmission Start Time* is defined as the time when a node can first start transmitting a packet. Setting the same transmission start time value for all the nodes in the network will cause packets that are transmitted using the same

TABLE III
SIMULATION PARAMETERS

Parameter	LoRaWAN	MoT
Duty-cycle	1%	1%
Number of Channels	3	3
Data Rate	Adaptive	Fixed
Transmission Start Time	Pseudo-Random	Time-Slot per node
Time Between Transmissions	Pseudo-Random + Minimum Delay	Multiple of the Duration of the Frame
Number of Downlink Windows	2	1
Downlink Window Delay	1 & 2 seconds consecutively	Duration of time-slot – Time of sub-slot

frequency channel and data rate to collide. We used this parameter to schedule the packet transmissions in the network.

• *Time Between Transmissions* is defined as the time a node has to wait before it can transmit a new packet. We used this parameter to schedule packet retransmissions.

• *Number of Downlink Windows* is defined as the number of idle and reception states a node has to schedule after each transmission state to receive an acknowledgment packet. If a node does not receive an acknowledgment during these windows, it considers that its packet has collided with another node's packet. We used this parameter to identify the operation pattern of the protocol.

• *Receive Window Delay* is defined as the amount of time the node waits before opening a downlink window. We used this parameter to identify the operation pattern of the protocol.

C. Simulation Model

The simulator creates a network of nodes, each node following the operation pattern of the protocol in question. Afterwards, the parameters discussed in section IV-B are used to identify the general network operation.

To model a LoRaWAN network, we set each node to start transmission after a random time that follows a Poisson distribution to ensure not all packets would collide on start. The time between each transmission was also set using a Poisson random time that exceeded the duty-cycle limitation. Since LoRaWAN utilizes adaptive data rate techniques to reduce power consumption, the data rate parameter was set to adaptive.

Modeling an MoT network using the simulator involves calculating the different node time-slot schedules as well as the duration of a single frame. This calculation is further described in [4]. Based on the parameters listed earlier, we set the transmission start time and time between transmissions to the scheduled time-slot and to the duration of the MoT frame respectively. At the end of each MoT time-slot is a single downlink acknowledgment packet. Therefore, a single downlink window was set to start after the difference between the duration of the time-slot and the time of sub-slot of the node.

D. Evaluation

We define the energy efficiency of a LoRa MAC layer by the number of successfully delivered packets utilizing a 1 Ah battery. In a contention-based protocol, packet collisions are the primary cause of unsuccessful packet delivery resulting in the retransmission of failed packets, thus reducing energy efficiency. A centralized-synchronous protocol, by definition, has minimal to zero collisions, rendering it theoretically more energy efficient than its counterparts. However, in some synchronous protocols, if time resynchronization is required too often, the energy efficiency is reduced dramatically.

For the following tests, we simulated each run ten times while varying the random seed for each run. Each random seed was kept constant between both protocols for every run to ensure fairness. We took the average of these runs and used it in the results. As illustrated in the following subsections, the lifetime of the synchronous protocol exceeded that of the contention-based protocol by up to a range of 3-4 times.

1) Single Node Energy Consumption: First, we used the simulator for each protocol to evaluate the total current consumption of a single node in the network during which it can successfully deliver a single 1-Byte packet. By doing so, this created a benchmark that we would use later to evaluate the energy efficiency. The benchmark results illustrated in Fig. 2 prove that a synchronous protocol, as compared to contention-based protocol, consumes less energy due to the deterministic nature of transmission/reception delays, leading to longer sleep times. However, it was noted that the consumption converges when the time between transmissions is increased, at which point the sleep time in both protocols is significantly longer than the other states. This benchmark gave us the current consumption of each protocol in an ideal situation when sending a single fixed-size packet.

2) Network Size and Energy Consumption: We then investigated the effect of the number of nodes in the network on the average current consumption of successfully transmitting a single packet with a fixed delay of 60 minutes. We ran multiple simulations while varying the number of nodes in the network and the size of the transmitted packet. As illustrated in Fig. 3, consumption increased exponentially with the increase in the number of nodes in contention-based protocols due to the increased collisions causing each node to retransmit the packet until the base station successfully receives the packet. While in the synchronous protocol, consumption was reasonably constant.

3) Operation Lifetime: Lastly, we investigated the efficiency of each protocol regarding battery lifetime. We simulated each network with a 1 Ah capacity battery, counting the number of packets each node successfully transmitted until the

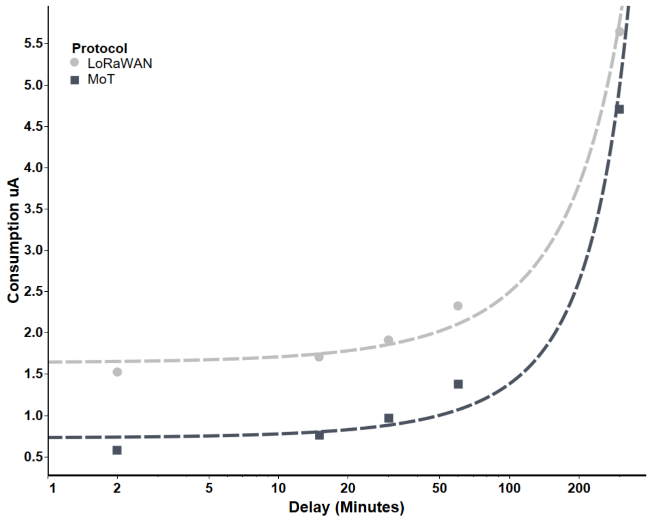

Fig. 2. Current consumption of successfully transmitting a single 1-Byte packet, with a single node in the network. (We used these results as a benchmark).

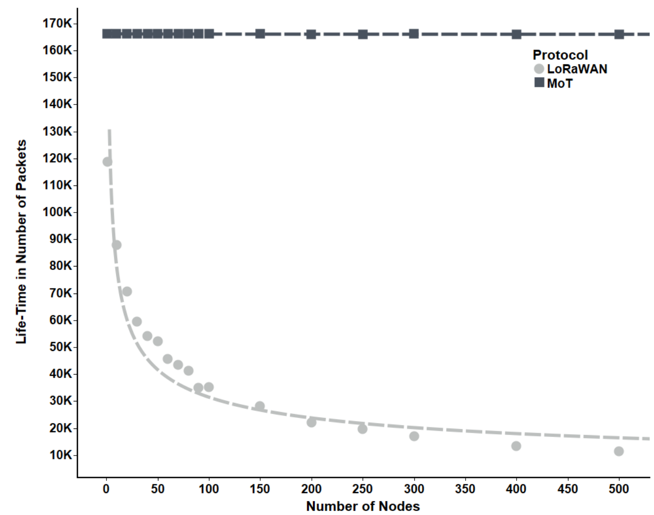

Fig. 4. Lifetime in packets of a single node using a 1 Ah battery, transmitting a single packet every 60 minutes, while varying the number of nodes in the network.

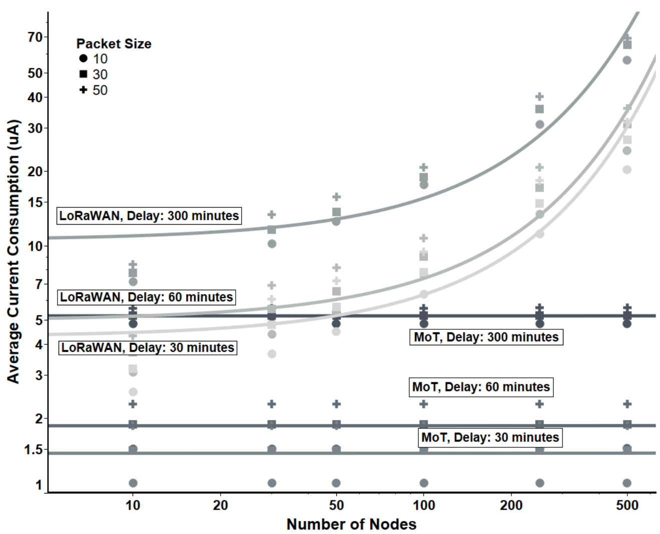

Fig. 3. Average current consumption of successfully transmitting a single packet, varying the payload size and number of nodes in the network.

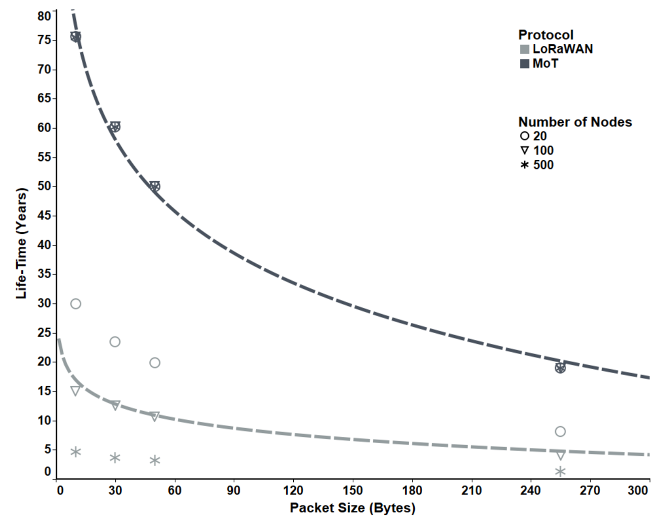

Fig. 5. Lifetime in years of a single node, transmitting one packet at different intervals while varying the number of nodes in the network.

battery was entirely drained. To estimate the lifetime in years, we allowed each node to transmit a single packet of 250-Bytes while varying the transmission delay and fixing the number of nodes in the network to 500. To estimate the lifetime by the number of packets, we varied the number of nodes and fixed the transmission delay to 60 minutes. Fig. 4 presents the lifetime of each protocol in the number of packets, and Fig. 5 presents the lifetime in the number of years.

V. Conclusion

In this paper, we used a tailored simulation tool to analyze the energy consumption of two LoRa-based protocol classes contention-based (LoRaWAN) and synchronous-based (MoT). We analyzed the energy performance with respect to network scale, transmission delay, and payload size.

We note that in applications in which the time between transmission is significantly longer, the energy performance slightly converges. However, when the network scale is increased, the point of convergence is significantly shifted forward in time, giving synchronous protocols an energy-saving advantage. We also note that the energy performance of centralized-synchronous protocols is unaffected by the number of nodes in the network. Therefore, we deduce that synchronous protocols are highly scalable compared to contention-based protocols regarding battery lifetime. We also conclude that the evaluated synchronous protocol outperformed the evaluated contention-based protocol up to four-fold in battery life, making it the protocol most suited for energy-critical applications. Further research is required on the effect of employing an adaptive transmission power scheme that in turn can improve the lifetime of LoRa-based networks in IoT.

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