MoT: A Deterministic Latency MAC Protocol for Mission-Critical IoT Applications

Galal Hassan, Hossam S. Hassanein
School of Computing
Queen's University, Kingston, ON, Canada
Email: {ghassan, hossam}@cs.queensu.ca

***Abstract*—With the growing demand on the IoT market and limited wireless resources, it is essential to fully utilize the available spectrum by improving the total throughput of the network. Many MAC protocols for IoT rely on pure ALOHA-based channel access. Being that these are contention-based the packet collisions cause a massive drop in both the throughput and packet delivery ratio. These, protocols are unsuitable for mission-critical applications which usually require long-range communication with guaranteed packet delivery and high throughput. In this paper, we propose a new hybrid scheduling-based protocol MAC on Time (MoT) that guarantees the delivery of all uplink packets in the network and addresses most of the important parameters required by mission-critical applications. MoT improves the utilization of the bandwidth capacity while providing deterministic latency and increased throughput when compared to other IoT MAC protocols. We then designed a simulator for MoT to allow us to compare its performance against that of LoRaWAN. This work provides valuable insight on the performance of both protocols and will aid future research.**

***Index Terms*—IoT; LoRa; LoRaWAN; Sigfox; Symphony Link; MAC; Deterministic Latency; Throughput; Mission Critical Systems; Packet Delivery Ratio; Media Access Protocol**

I. Introduction

The Internet of Things (IoT) is used in a multitude of applications such as monitoring, tracking, and industrial instrumentation, thus enabling it for mission-critical applications. With the critical nature of these applications, increasingly restrictive requirements elevate the scale of challenges associated with wireless communications [1]. These requirements include guaranteed message delivery, high throughput, long range, and deterministic latency [2]. Such challenges hinder the network performance and are distributed among the different layers of the network architecture, starting with the limitations of the physical (PHY) layer. A PHY layer defines the maximum bitrate and communication range among other network defining properties. Hence, Mission-critical applications require the use of a PHY layer that permits such properties. One of the main physical layer technologies is LoRa [3], which provides an extended range of coverage with low power consumption at the cost of limited bitrate. Since mission-critical IoT applications do not rely on high bitrate [4], LoRa is considered to be one of the most suitable PHY layer technologies for such applications [5].

Medium access control (MAC) has been at the center of attention recently to address the primary requirements of guaranteed delivery. Multiple MAC layer protocols have been proposed that work on top of a LoRa PHY layer, such as LoRaWAN [6], and Symphony Link [7]. Each protocol promises a Low Power Wide Area Network (LPWAN) however, each has shortcomings when it comes to mission-critical applications. LoRaWAN is contention-based, and absolute packet delivery is not guaranteed, rendering it unsuitable for mission-critical application. Symphony Link, is a synchronous protocol, but it employs a very restrictive environment that hinders its performance in a mission-critical environment. To address these shortcomings we developed MoT, a new MAC layer protocol built on top of a LoRa PHY layer. MoT is a centralized synchronous protocol that improves the bandwidth capacity four times beyond that of LoRaMAC.

Our contributions can be summarized as follows. First, we design a new MAC layer protocol that addresses the main challenges that remain unresolved by the current protocols. We also develop a simulation framework for our protocol and LoRaWAN. Finally, we conduct extensive simulation tests for both MoT and LoRaWAN and analyze the performance of both protocols under the same conditions.

The remainder of this paper is organized as follows. Section II outlines the different challenges brought forward to MAC protocols due to the rise of the IoT. Section III discusses the PHY layer of LoRa as well as an overview of LoRaWAN. Section IV presents the details of the proposed protocol MoT. Section V discusses the evaluation metrics and experiment setups. Section VI evaluates the results. Finally, in section VII, our conclusions and final remarks are presented.

II. MAC Protocol Challenges

Due to the range of applications employed in IoT, new challenges have been introduced that are not fully addressed by the current protocols. Our main motivation behind the design of MoT was to address the following six challenges.

1) Packet Delivery Ratio: One of the main requirements of any mission-critical application is guaranteed packet delivery. Therefore, any MAC protocol used in such applications must have packet-delivery ratio of 100%. MoT eliminates packet collisions by precise time-slot scheduling, as well as by acknowledging all uplink messages, this guarantees packet delivery.

2) Bandwidth and Data Rate: Data rate is the number of bits transferred in a given time unit, and bandwidth is a range of frequencies in a radio spectrum that is used as a single

978-1-5386-2070-0/18/$31.00 ©2018 IEEE

Authorized licensed use limited to: Queen's University. Downloaded on August 05,2020 at 13:10:18 UTC from IEEE Xplore. Restrictions apply.

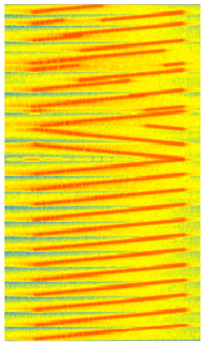


Fig. 1. LoRa Modulation

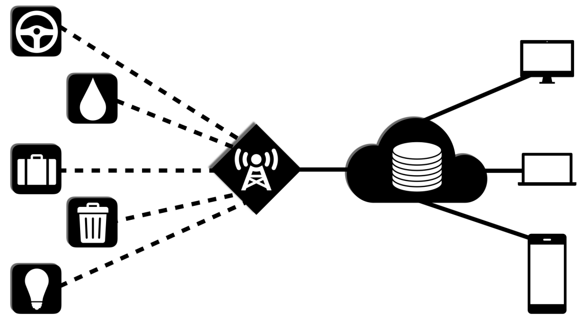


Fig. 2. MoT System Architecture

transmission channel. A higher capacity bandwidth allows more bits to be transferred at a given time, which in turn increases the data rate. Since MoT uses LoRa as the underlying technology for the PHY layer, there is a trade-off between data rate and communication range [5].

3) Battery Life: Due to the large number and diversity of IoT device hardware, one technology is unable to overcome the energy consumption challenge [8]. In a typical IoT application, a multitude of devices are connected, each equipped with a limited number of batteries that limit the energy resources available to that device. Due to the vast number of devices employed, it is often challenging to replace these batteries for each device upon depletion. MoT ensures a maximum battery life up to 30 years by minimizing the time in which a device is required to remain in a listening state until a packet is received.

4) Range: Covering a wide geographical area with fewer devices reduces the implementation, operations and maintenance cost of a network. Increasing the range of communication entails an increase of transmission power, which in turn reduces battery life. It becomes important to ensure that a wireless technology adapted for IoT would cover a wide range while minimizing the transmission power requirements. MoT currently covers up to five km in urban areas and 40 km in rural areas, while ensuring minimal cost during the lifetime of the device [9].

5) Latency: Instantaneous communication requires lower latency on the communication network. In mission-critical applications, it is necessary to identify the latency ahead of transmissions. However, due to the changing nature of a network using asynchronous access schemes, latency is non-deterministic. MoT ensures deterministic latency ahead of transmission because of its centralized scheduled nature.

6) Throughput: Having a device that can transmit a large amount of data as often as possible is ideal yet is unmet in IoT. ALOHA-based technologies are known for their low throughput due to packet collisions. MoT capabilities include high throughput by reducing packet collisions and synchronizing transmissions.

III. Background

LoRa PHY employs a spread spectrum modulation scheme that uses a continuously varying chirp to encode information. This scheme provides a simpler receiver design and therefore lower power requirements [10]. Fig. 1 represents a LoRa modulated signal as measured by our software-defined radio. Long-range communication is achieved by the ability of a LoRa receiver to decode transmissions 19.5 dB below the noise floor level [11]. LoRa PHY can be used with any MAC layer. However, LoRaWAN is the MAC layer protocol sanctioned by the LoRa Alliance. A LoRaWAN network uses the star of stars topology architecture, in which a single gateway communicates with multiple end nodes and relays this information back to a network server over an Ethernet backhaul [12]. The current LoRaWAN network specification describes three classes of end devices: Class A, Class B, and Class C. Each device class compromises either battery lifetime or downlink latency [5].

1) Class A: These devices have scheduled uplink transmission windows; after each uplink transmission, the device opens up two short downlink windows. This class has the lowest power consumption with the highest latency.

2) Class B: These devices have multiple scheduled downlink windows, that reduces the downlink latency while increasing the power consumption.

3) Class C: This class of devices uses the most power and has the lowest latency, due to using continuous receive windows.

IV. Mac on Time (MoT)

MoT is designed to resolve multiple dilemmas related to MAC protocols: namely, reduce energy consumption, support good scalability, ensure fairness, and maximize channel utilization. The strength of MoT relies on overcoming clock drifts while using a channel-access method based on centralized-scheduling protocols.

An MoT network uses a star topology architecture, in which nodes periodically communicate information to a centralized base station, that then relays this information to a back-end server. Fig. 2 illustrates the system architecture in a local MoT network. Between each communication, a node idles for an extended period, the duration of which is determined by the centralized base station and conveyed to each node in the acknowledgment of each report. We expect a large number of

Authorized licensed use limited to: Queen's University. Downloaded on August 05,2020 at 13:10:18 UTC from IEEE Xplore. Restrictions apply.

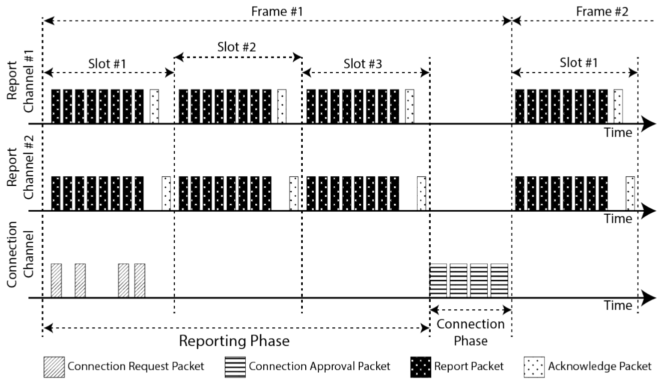


Fig. 3. Basic MoT Allocation Scheme

nodes to be implemented in a single network; scalability is an important consideration.

In the following subsections, we discuss how MoT maximizes channel utilization while providing deterministic latency.

A. MoT Design Details

MoT can be described as a hybrid protocol, one that combines contention-based and TDMA-based protocols. It is a centralized, guaranteed-access, wireless MAC protocol using a base station for coordinating the channel access time-slots in a semi round-robin manner. Hence a star topology network is required. Every report is acknowledged by the base station to confirm that message delivery is reliable. MoT is designed to run on top of a LoRa PHY layer with the following six modem settings: Spreading Factor of 10, Bandwidth of 125 kHz, Coding Rate of 4/5, with an explicit header, CRC enabled, and a preamble of 8 symbols. These settings give us a link budget of 152 dB and receiver sensitivity of -132 dBm.

One of the main features of MoT is the scheduling mechanism used by the base station to utilize the maximum capacity of a single channel, allowing MoT to produce superior throughput. The base station is capable of receiving multiple packets at the same time over different logical and physical channels to ensure that a single node can transmit packets as frequently as possible without violating the duty cycle limitations. A physical channel is one that is defined by a difference in carrier frequency; multiple logical channels would use a single physical channel, but then with different modulation parameters, this is possible through the modulation/demodulation technique used by the PHY layer.

The base station divides a single channel into a reporting phase and a connection phase. The reporting phase is subdivided into multiple time-slots with each time-slot divided into multiple sub-slots. Each sub-slot represents a report packet of a fixed size. At the end of a time-slot, the base station acknowledges all the packets received during this time-slot. During the connection phase, the base station individually approves/denies each connection request that it received during the reporting phase.

MoT allows one node to report only once per frame to safeguard the deterministic latency unique to MoT. However, MoT allows a variable packet size for each node. Consequently, one node can occupy one or more sub-slots based on the size of the payload required to be transmitted. Once a node is connected to the network, it gets assigned a number of sub-slots by the base station; this is initiated by the node transmitting a connection request packet on the connection channel indicating the number of sub-slots required. If the node needs to change the size of the payload at any time, it disconnects and reconnects to the network. During each time-slot, each node will transmit a packet only during its assigned sub-slot(s), rendering the reporting phase free of collisions between packets. The basic scheme is depicted in Fig. 3.

B. Time and Scheduling

One challenge of most TDMA protocols is resynchronizing clocks between the different nodes and the base station due to clock drifts [13]. This drift is caused by the dissimilar hardware used for the different types of nodes as well as the environmental factors in which this node is operating. A case in point, the crystal oscillators of a node would cause a time drift of up to 0.18 seconds every hour [14]. MoT does not require clock synchronization between the different nodes and the base station. Instead, a base station in MoT calculates a time delay for each node between reports. To further protect against time drifts, a tolerance value Tol is applied to different parts of a frame. When a base station is first initialized, it starts calculating the frame schedule based on the different parameters set by the application; this includes the acknowledge time on air T_{ack}, payload time on air T_{pl}, duration of one time-slot $T_{time-slot}$, and the number of sub-slots per time-slot n_{ss}. These values remain constant over the lifespan of the network. There are some values that are recalculated by the base station during network operation; these values include the current number of slots per frame n_{slots}, duration of the reporting phase T_{rp}, duration of the connection phase T_{cp}, and time until the start of time-slot.

1) The Time On Air: This is the time required for one packet of a certain size to be transmitted over the PHY layer. This calculation is based on the PHY layer modulation parameters and described in (1-4) [3]. The LoRa PHY layer modulates the payload bytes (PL) into multiple symbols $n_{payload}$ based on the spreading frequency (SF), bandwidth (BW), coding rate (CR), the presence of an explicit header (H), and whether or not the low data-rate optimization is enabled (DE). The time on air of one symbol T_{sym} can be calculated using the SF and BW; using T_{sym} along with the number of preamble symbols $n_{preamble}$ allows us to calculate the time on air for the preamble $T_{preamble}$, this, in turn, gives us the ability to calculate the time on air for both T_{ack} & T_{pl}.

$$T_{sym} = \frac{2^{SF}}{BW} \tag{1}$$

$$T_{preamble} = (n_{preamble} + 4.25) \times T_{sym} \tag{2}$$

$$\begin{aligned} n_{payload} &= 8 + max(\\ ceil&((\frac{8PL - 4SF + 28 - 16 - 20H}{4(SF - 2DE)})(CR + 4), 0)) \end{aligned} \tag{3}$$

Authorized licensed use limited to: Queen's University. Downloaded on August 05,2020 at 13:10:18 UTC from IEEE Xplore. Restrictions apply.

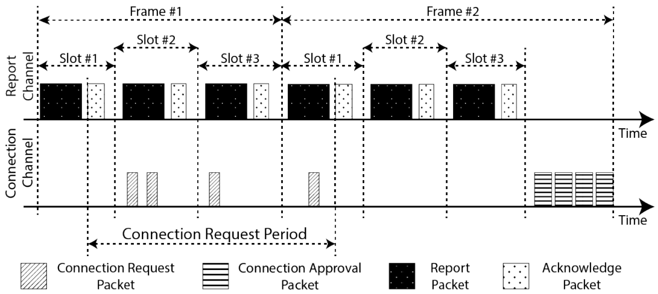


Fig. 4. Connection Phase Timing Calculation

$$T_{oa} = T_{preamble} + (n_{payloadsymbols} \times T_{sym}) \tag{4}$$

2) The Duration of One Time-Slot: To ensure fair access to the base station on a certain channel, the T_{ack}, including the tolerance value Tol, should be a certain percentage of the total $T_{time-slot}$. This percentage is the duty cycle limitation (DC) of the region in which the MoT network is operational. Eq. (5) allows us to calculate $T_{time-slot}$ in the presence of a DC.

$$T_{time-slot} = \frac{T_{ack} \times Tol}{DC} \tag{5}$$

3) The Number of Time-Slots per Reporting Phase: For the base station to ensure the least amount of time between each frame, it utilizes the $n_{channels}$ available before increasing the number of time-slots in each frame. Based on the number of currently connected nodes n_{nodes}, the base station can calculate n_{slots} using (6).

$$n_{slots} = \frac{n_{nodes}/n_{ss}}{n_{channels}} \tag{6}$$

4) The Duration of the Connection Phase: The connection phase is only part of a frame when the base station receives connection requests during the Connection Request Period CR_P. The CR_P is the period of time between the start of the acknowledgement packet of the first slot of this frame and the start of the acknowledgement packet of the first slot of the previous frame, this is illustrated in Fig. 4. Eq. (7) is used to calculated T_{cp} factoring in the number of requests $n_{requests}$ received during CR_P, as well as the time on air of the approval packet T_{app}.

$$T_{cp} = T_{app} \times n_{requests} \tag{7}$$

5) The Duration of the Reporting Phase: This is dependent on both the n_{slots} and the $T_{time-slot}$, assuming no connection requests were received; as a result, the reporting phase duration consumes the full duration of the frame.

6) The Duration of the Frame: This is the total of the T_{rp} & Tcp; it is also defined as the latency of an MoT network as it represents the time until a node can send another packet.

7) Time Until a Time-Slot Restarts: The base station calculates the remaining time until a time-slot starts, this happens on two occasions: when a new node joins the network T_α and at the end of each time-slot T_β. These values are then used by each node along with its sub-slot index SS_i to calculate the time at which it can transmit a report packet. The slot index $Slot_i$ is the position of a time-slot inside the reporting phase. Eq. (8) is used at the beginning of the connection phase to initialize the remaining duration of the connection phase T_{rcp}, followed by (9) and (10), which are used once for each connection approval packet to be sent. Eq. (11) is used at the beginning of each frame to initialize the remaining duration of the frame T_{rf}, followed by (12) and (13), which are used once for each slot in the time frame.

$$T_{rcp} = T_{cp} \tag{8}$$

$$T_{rcp} = T_{rcp} - T_{ack} \tag{9}$$

$$T_\alpha = T_{rcp} + (T_{time-slot} \times Slot_i) \tag{10}$$

$$T_{rf} = T_{frame} \tag{11}$$

$$T_{rf} = T_{rf} - (T_{time-slot} \times (Slot_i + 1)) \tag{12}$$

$$T_\beta = T_{rf} + (T_{time-slot} \times Slot_i) \tag{13}$$

V. Implementation and Experimentation

All our tests were compliant with the FCC and ETSI regulatory compliance requirements [15], [16], ensuring a fair comparison between MoT and LoRaWAN. In addition, we compared MoT with a class A LoRaWAN device; this class of LoRaWAN has one uplink window followed by two downlink windows. To discuss the capabilities of MoT, it was essential to test the throughput in a large-scale implementation, unfortunately, this was not feasible because of the cost. Therefore, we designed a simulator to measure the throughput of MoT and used LoRaSim [17] to evaluate the performance of LoRaWAN in similar conditions and compared the results. We discuss the different evaluation metrics and the simulation setup as follows.

A. Evaluation Metrics

We represent the efficiency of a MAC protocol as the network throughput against both the network capacity and the latency of the network. Given that the efficiency of a protocol varies with the channel load we considered the efficiency of each protocol at different channel loads.

We define the latency of the MAC layer as the total time between when the upper layer forwards a payload to the MAC layer and when the MAC layer transmits the packet using the PHY layer. In MoT, the latency is the transmission delay set by the size of a frame.

We evaluated a single device throughput abiding by the EU's 1% channel access restriction, this entails that a single device would not be able to transmit a consecutive packet unless it waits for a duration of 99 times the time on air it used to transmit the first packet. This metric is limited more to the PHY layer than the MAC layer, and since both MoT and LoRaWAN use the same PHY layer, we expected the single device throughput to be fairly equal. Keeping this in mind, we investigated the throughput of each protocol while considering packet collisions. Since MoT is contention free by definition, we anticipated our protocol to outperform LoRaWAN regarding network throughput when factoring in packet collisions from multiple nodes. The channel capacity

Authorized licensed use limited to: Queen's University. Downloaded on August 05,2020 at 13:10:18 UTC from IEEE Xplore. Restrictions apply.

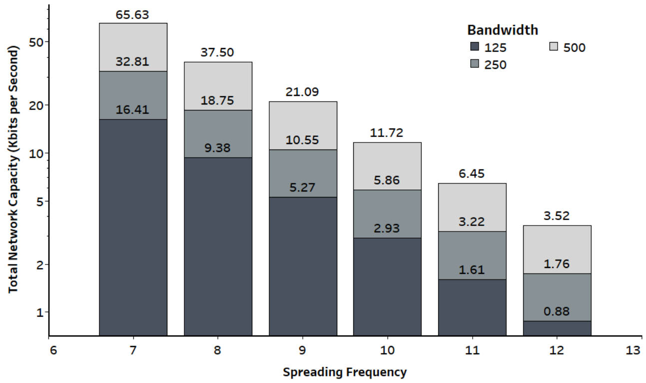


Fig. 5. The channel capacity of MoT using BW 125, 250, and 500.

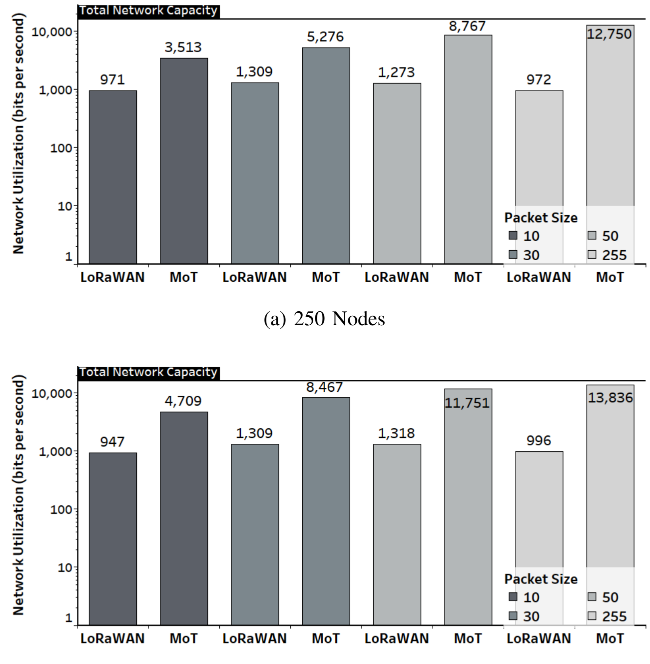
is defined as the theoretical maximum throughput of a channel. In a typical LoRaWAN network, the base station can decode multiple packets at the same time, given that each packet is using a different spreading frequency; this brings the total theoretical capacity of a single 125 kHz channel to 12,025 bps [2]. With three 125 kHz channels, the total network capacity becomes 36 kbps. Since currently, MoT does not support multiple spreading frequencies on a single channel, the minimum total channel capacity of a MoT network with three channels is 16,406 bps. Fig. 5 illustrates the total network capacity of MoT using different modulation parameters, all assuming a network with three channels.

B. Simulation Setup

LoRaSim, which is described in more detail in [11], models only the uplink part of LoRaWAN; therefore, we modified the simulator to consider the downlink periods before retransmitting another packet.

We developed the simulation tool MoTSim using SimPy [18], a discrete-event simulator using Python. With MoTSim, we were able to test the implementation of a large-scale MoT network that has a single base station and a different number of nodes. In the development of MoTSim, we purposely ignored the connection phase and assumed that all nodes were connected to the network. Each experiment started by defining the parameters in which the network would operate: the total number of nodes, payload size, and simulation duration. Using these parameters, MoTSim starts by calculating the frame schedule including T_{ack}, T_{pl}, n_{ss}, $T_{time-slot}$, and n_{slots}. It continues by creating an instance of each node and scheduling it to transmit with constant radio parameters. Since MoTSim does not yet support adaptive data rate, it is important that all nodes have the same BW and SF during setup for each experiment.

To evaluate the performance of MoT against LoRaWAN, we ran several simulation tests of 3,600 seconds each. At the end of each simulation, we calculated the throughput of the network over the full duration of the simulation, the number of dropped packets due to collision or path loss, and the total energy consumed by the network. In the following section, we present and discuss the results of these simulations.



(a) 250 Nodes

(b) 1000 Nodes

Fig. 6. The throughput of LoRaWAN and MoT across different packet sizes.

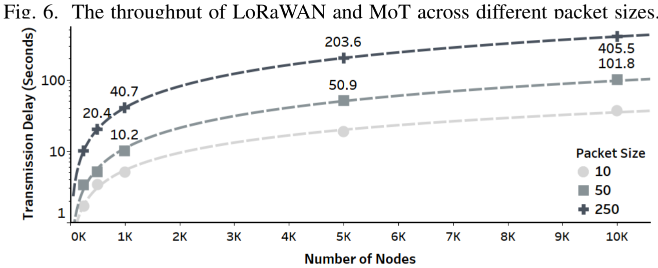


Fig. 7. Latency of MoT across different packet sizes and number of nodes.

VI. Evaluation

We performed multiple simulations to evaluate the performance of both protocols using the metrics discussed earlier in section V-A.

A. Throughput Evaluation

We first compared the throughput of MoT with three channels to LoRaWAN with fixed data rate as the experimental setups with a different number of nodes and packet sizes. Fig. 6 shows the comparison between the throughput achieved. It can be seen that both protocols do not utilize the full channel capacity; one common factor that affects both protocols is the time on air wasted on PHY layer transmissions, including the preamble, header, and CRC. One that caused the underutilization in LoRaWAN is the number of collisions due to the increased number of nodes transmitting. MoT has several contributing factors causing the underutilization of the network: the lost capacity due to the acknowledge packets over other channels, the tolerance value used in the network, and the empty slots un-occupied by nodes. From this test regarding channel utilization, MoT surpassed the performance of LoRaWAN.

Authorized licensed use limited to: Queen's University. Downloaded on August 05,2020 at 13:10:18 UTC from IEEE Xplore. Restrictions apply.

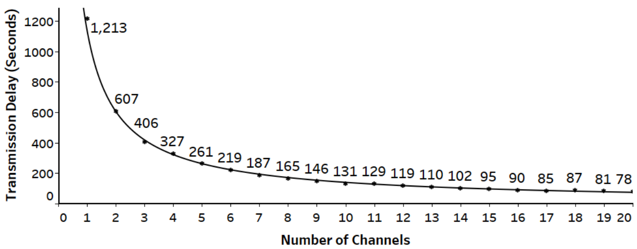


Fig. 8. The relationship between the number of channels and Latency using BW of 500, 10,000 nodes, and 250 bytes of payload.

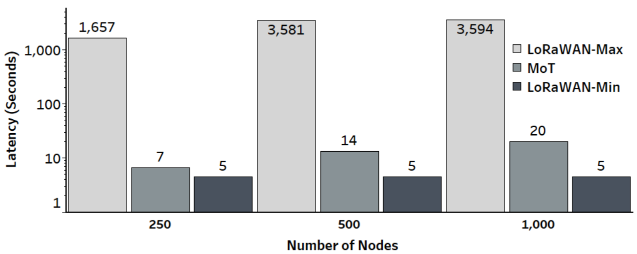


Fig. 9. A comparison between the latency of MoT and LoRaWAN with different number of nodes and a fixed packet size of 10 bytes.

B. Latency Evaluation

We investigated the effect of the number of nodes in the network on the transmission delay of MoT with a constant payload size of 10, 50, and 250 Bytes. Fig. 7 shows how the transmission delay is affected by the number of nodes in a single network using BW of 500 kHz, with the shortest latency of 1.7 seconds. We then examined the effect of the number of channels on the latency, which improves by increasing the number of channels; though, the improvement starts saturating after having six channels. This is illustrated in Fig. 8. Latency for a class A LoRaWAN device is a minimum of 1-2 seconds disregarding channel access regulations and the number of nodes in the network. This number increases when considering packet collisions. Fig. 9 depicts the comparison in latency between LoRaWAN and MoT when considering a duty cycle of 1%, BW of 125 kHz, payload size of 10 bytes, and presence of collisions. From this latency test, the performance of MoT exceeds that of LoRaWAN.

VII. Conclusion

One of the challenges in wireless protocols for IoT is the ability to utilize the channel capacity fully. In this paper, we propose MoT, a MAC layer protocol that provides deterministic latency and utilizes the channel capacity four times more than that of LoRaWAN. With the aid of a simulator which we developed, we were able to test the limitations of both LoRaWAN and MoT. After analyzing the results, we conclude that MoT outperforms LoRaWAN in both latency and throughput. All our simulations used three channels for MoT; however, due to the nature of the PHY layer that MoT is designed for, more channels can be used to enhance the performance of MoT further. We found that there is a direct correlation between the latency of MoT and the number of nodes in the network. We improved the latency by simulating a different number of channels and found that the improvement starts to saturate at a certain number of channels. Further testing is needed to evaluate the power consumption of MoT against other protocols.

Acknowledgment

This research is supported by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC) under grant number: STPGP 479248.

References

[1] A. Lavric and V. Popa, "Internet of things and lora; low-power wide-area networks: A survey," in *2017 International Symposium on Signals, Circuits and Systems (ISSCS)*, July 2017, pp. 1–5.

[2] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A study of lora: Long range & low power networks for the internet of things," *Sensors*, vol. 16, no. 9, p. 1466, 2016.

[3] SEMTECH, *LoRa Modem*. [Online]. Available: https://www.semtech.com/uploads/documents/LoraDesignGuide_STD.pdf

[4] G. Sakya, V. Sharma, and P. C. Jain, "Analysis of smac protocol for missioon critical applications in wireless sensor networks," in *2013 3rd IEEE International Advance Computing Conference (IACC)*, Feb 2013, pp. 488–492.

[5] J. de Carvalho Silva, J. J. P. C. Rodrigues, A. M. Alberti, P. Solic, and A. L. L. Aquino, "Lorawan; a low power wan protocol for internet of things: A review and opportunities," in *2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech)*, July 2017, pp. 1–6.

[6] Lorawan specification 1.1. [Online]. Available: https://lora-alliance.org/

[7] Symphony link vs. lorawan. [Online]. Available: www.link-labs.com

[8] W.-J. Shyr, C.-M. Lin, and H.-Y. Feng, "Development of energy management system based on internet of things technique," *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, vol. 11, no. 3, pp. 207–210, 2017.

[9] U. Noreen, A. Bounceur, and L. Clavier, "A study of lora low power and wide area network technology," in *2017 International Conference on Advanced Technologies for Signal and Image Processing (ATSIP)*, May 2017, pp. 1–6.

[10] SEMTECH, *LoRa Modulation Basics*. [Online]. Available: www.semtech.com/uploads/documents/an1200.22.pdf

[11] M. Bor, U. Roedig, T. Voigt, and J. Alonso, "Do lora low-power wide-area networks scale?" in *MSWiM '16 Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*. ACM Press, 11 2016, pp. 59–67.

[12] LoRa-Alliance-Technical-Marketting-Workgroup, "Lorawan what is it?" 2015. [Online]. Available: https://lora-alliance.org/

[13] R. Tjoa, K. L. Chee, P. K. Sivaprasad, S. V. Rao, and J. G. Lim, "Clock drift reduction for relative time slot tdma-based sensor networks," in *2004 IEEE 15th International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE Cat. No.04TH8754)*, vol. 2, Sept 2004, pp. 1042–1047 Vol.2.

[14] D. Wagner and R. Wattenhofer, *Algorithms for Sensor and Ad Hoc Networks: Advanced Lectures*. Berlin, Heidelberg: Springer-Verlag, 2007.

[15] E. T. ETSI, "Electromagnetic compatibility and radio spectrum matters (erm); short range devices (srd); radio equipment to be used in the 25 mhz to 1 000 mhz frequency range with power levels ranging up to 500 mw," *European harmonized standard EN*, vol. 300, no. 220, p. v2.

[16] E. Recommendation, "70-03 relating to the use of short range devices (srd)," *Version of*, vol. 18, 2009.

[17] Lorasim. [Online]. Available: http://www.lancaster.ac.uk/scc/sites/lora/lorasim.html

[18] T. SimPy. Simpy. [Online]. Available: https://simpy.readthedocs.io/en/latest/

Authorized licensed use limited to: Queen's University. Downloaded on August 05,2020 at 13:10:18 UTC from IEEE Xplore. Restrictions apply.