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Time-slotted LoRa MAC with variable payload support

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ABSTRACT

LoRaWAN is an upcoming Low Power Wide Area Network (LPWAN) technology for Internet of Things implementations in various application domains. Despite its various advantages, LoRaWAN employs an Aloha-based MAC, which in terms of performance cannot guarantee high packet delivery ratio and low latency. To overcome this issue, we propose a time-slotted scheme, called TS-VP-LoRa, which supports multiple transmission times and packet sizes at the same time. In TS-VP-LoRa, scheduling is coordinated by the LoRa gateway, broadcasting beacon frames periodically for the synchronization of LoRa end-devices. A channel hopping mechanism is also proposed in order to minimize the occurrence of collisions and to evenly split the transmission load among all channels. TS-VP-LoRa is evaluated and compared to three other MAC-layer schemes in single gateway simulation scenarios with up to 500 nodes. The proposed scheme has proven to achieve low latency with high packet delivery ratios, significantly minimize collisions and maintain a relatively low energy consumption despite the scaling of the LoRa network.

1. Introduction

LPWAN radio technologies fulfilled the need for long range, low power, and low financial cost communication solutions. LPWAN enabled the remote data collection from sensor devices located far from the base stations and simplified industrial applications such as the asset tracking in terms of required network infrastructure.

LoRa is a proprietary LPWAN technology based on the known Chirp Spread Spectrum modulation. It can achieve long communication ranges of up to several kilometers with Line-of-Sight and it presents remarkable resilience against interference and Doppler effects. LoRa has the ability to trade signal sensitivity with data rate. Longer communication distances can be achieved by sacrificing the data rate. As a consequence, longer transmission times – and thus higher energy consumption – are required to send the same amount of data to longer distances. This trade-off between data rate and sensitivity is controlled using a radio parameter called Spreading Factor (SF) which typically ranges from 7 to 12. Higher SF values improve the sensitivity but decrease the data rate. The gateways can receive transmission from different SF at the same time even though inter-SF interference may sometimes occur [1]. Other typical parameters that affect the transmission time is the channel bandwidth and the coding rate. Lower channel bandwidths and higher coding rate values increase the transmission time in favour of better sensitivity (i.e., longer range) and increased resilience to bit errors, respectively.

LoRaWAN is currently one of the top-used LPWAN protocols in many different IoT applications domains such as precision agriculture [2,3] asset tracking, building automation etc. [4]. It relies on the LoRa physical layer, but unlike LoRa, it is an open standard maintained by the LoRa Alliance. LoRaWAN distinguishes three classes of operation; Class-A consists of energy constrained devices which are used to report events to the gateways, Class-B enables synchronized network-initiated downlink frames in order to open extra receive windows for the nodes, and Class-C is used for devices with sufficient energy resources that can constantly listen for received data. Since LoRaWAN bases its uplink operation on an Aloha-based MAC, it cannot guarantee high packet delivery ratios especially when the traffic gets high or if many downlink transmissions are required for acknowledgements [5]. This is not acceptable for many industrial applications that require high reliability and low latency such as predictive maintenance or health care applications [6–8].

To overcome the aforementioned issue, researchers have proposed time-division and synchronized solutions based on LoRa. These solutions divide the time in timeslots whereas a single transmission is allowed per slot. Due to the multiple configurable parameters of the LoRa radios, the researchers have come to a compromise regarding the size of the timeslots. Thus, only one combination of SF, channel bandwidth, coding rate, and packet size is considered except TS-LoRa [9] where all SFs can be supported by deploying additional 1-channel gateways. The channel bandwidth and the coding rate are not an important issue because they are usually fixed to 125 kHz (e.g., in LoRaWAN)

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and to 4/5, respectively. However, it is important for a time-slotted approach to support as many SFs and packet sizes as possible in order to decrease the waste of time and energy resources and, thus, increase the network capacity.

In this paper, we propose a time-slotted scheme, called TS-VP-LoRa, which supports multiple SFs and packet sizes at the same time. TS-VP-LoRa exploits 3-dimensional superframe structures where the first dimension is the time, the second is the SF, and the third is the payload size. The approach is intra-SF collision-free because each timeslot is unique for each node in the network and different channels are assigned per frame to avoid inter-SF interference. A channel hopping mechanism is also applied to avoid congestion and ensure fairness among the nodes. Details of how TS-VP-LoRa works are given in Section 3. The approach is evaluated and compared to other approaches using simulations in Section 5. Finally, Section 6 concludes the paper and presents ideas for future work.

The contributions of this work are summarized as follows:

1. A multi-SF and multi-payload time-slotted frame architecture is presented.
2. A channel hopping mechanism is adopted to avoid burst of collision due to congested channels and evenly split the transmission load among all channels.

2. Related work

Due to the extremely high number of studies in the area of LoRa and LoRaWAN, this section surveys only the time-slotted and synchronized approaches. For a more exhausted literature review, the reader may look at some recent survey articles [5,10–13].

Synchronized approaches can considerably reduce or even eliminate collisions but require periodic beacon transmissions so that the nodes wake up at specific timeslots to transmit data. The transmissions can be either Aloha-based (i.e., Slotted-Aloha) or be scheduled by the network server. Autonomous and mesh approaches have also been proposed. The following subsections present the main ideas of such works.

2.1. Synchronized Aloha approaches

Polonelli et al. [14,15] assumed that the synchronization constitutes a LoRaWAN overlay where beacons are periodically transmitted by the gateway. The authors considered fixed-size payload, SF, and channel bandwidth settings while performing a number of experiments to assess the network throughput. The authors report a two times higher throughput compared to typical LoRaWAN.

Chasserat et al. [16] present another Slotted-Aloha scheme leveraging the class-B functionality of LoRaWAN. The proposed scheme divides the time in slots where uplinks and downlinks can be accommodated. Sensing for possible downlinks takes place before the uplink transmission in each slot. As with the previous study, the authors report a nearly double throughput for twice the number of End-Devices (EDs), in comparison with the Class-A functionality.

In [17], a new MAC-layer is proposed based on synchronized beacons that are transmitted by the gateways. Every frame is divided into sub-frames and every sub-frame is further divided into slots. One slot is dedicated for synchronization and the rest are for asynchronous uplink or downlink slots for nodes' confirmed or unconfirmed transmissions. The transmissions are performed in an Aloha-like way. The beacons are transmitted in every channel using every SF in a cyclic manner at the start of any frame and sub-frame. The beacons are also used for carrying downlink information (i.e. each beacon carries information about how to use the uplink/downlink slots in that corresponding sub-frame) which the EDs use later to select the channel and the SF for transmission. Using simulations, the authors state that the approach improves the overall network performance considerably compared to LoRaWAN.

2.2. Scheduling approaches

Haxhibeqiri et al. [18] present a low overhead synchronization and scheduling scheme for LoRaWAN, where the network server schedules a node's transmissions by sending a list of time slots when the node is allowed to transmit. These slots are encoded in a probabilistic data structure using Bloom filters to reduce the size of the transmitted message. A node can receive this information by sending sync requests which are processed and replied by the network server. The transmissions are based on a slotted-Aloha scheme, thus, collisions are not eliminated. However, the study reports high performance gains compared to the Aloha-based solution. An implementation-focused paper on the same study has recently been published by the authors to show the potential of the approach [19].

Lee et al. [20] schedule the nodes' transmissions based on their SF and the available channels. The idea is to allocate same-SF transmissions in different channels and then schedule them during the same time-slotted period. If the number of transmissions of the same SF is higher than the number of channels, consecutive slots are allocated. Assuming an equal frame size for each channel a group acknowledgement technique is used for all the nodes. The simulation results show that the approach outperforms Aloha when many channels are available.

A number of studies examine the scenario where the gateway is not available at all times, thus, the nodes have to buffer the monitoring data and transmit it when the gateway becomes available. However, due to the short time availability of the gateway, many collisions may occur. The main idea of these studies is to compute a schedule of transmissions in slots and send this schedule to the nodes in an efficient way. This is not a trivial task due to the low bitrate of LoRa transceivers and to the duty cycle restrictions. The studies consider the computation of the schedule to be done as long as the nodes register to the network [21] or by finding an optimal schedule as long as all nodes' information has been collected [22,23]. The second approach is more efficient in terms of data collection time but less reliable when the network size is high.

Finally, Finnegan et al. [24] propose a scheduling approach where some end-devices are instructed to delay their transmissions in order to avoid collisions. This is attempted by allowing the network server to keep records of transmissions through time intervals and then run a collision prediction algorithm to scatter overlapping transmission to different timeslots. The authors conduct a series of simulations and report a packet delivery ratio enhancement of about 15% on average compared to legacy LoRaWAN. The drawback of the approach is that a high number of downlinks need to be sent in a short time which may put extra burden on the already limited downlink capabilities of LoRaWAN networks. Moreover, since no time-synchronization is applied, the nodes' clock may quickly drift over the instructed timeslot borders.

2.3. Autonomous approaches

Since the transmission of the schedule is a hard task in LoRa networks, researches have proposed more sophisticated solutions to relieve the network from the scheduling computation burden. This is done through autonomous techniques where a number of settings are decided during the registration of the nodes.

Zorbas and O'Flynn [25] present an autonomous way to create a time schedule for a given number of nodes with known device identifiers (DevEUI). Having this information, a central unit (e.g., the network server) can compute a number of slots such that no collision exists between the devices on the same channel. The advantage of the approach is that only the total number of slots is required to be communicated to the nodes to determine their unique slot number. Thus, the number of bytes broadcasted by the gateway is minimal. The disadvantage of the solution is that many slots are left unutilized in between successive transmissions which may considerably increase the frame size as the number of nodes in the network increases.

This problem is fixed in [9] by allowing the network server to manipulate the node's unique address in the network using a crypto-hash function and a simple modulo operation. The authors report very high delivery ratios of over 99% by conducting simulations and experiments. The energy consumption is also reduced compared to LoRaWAN in scenarios with high traffic.

2.4. Mesh approaches

Multi-hop LoRa mesh solutions are proposed in a number of studies [26–28]. These studies propose solutions that encompass a time-slotted channel hopping strategy (TSCH) [26] or rely on the functionality of IEEE802.15.4-based standards, such as the 6TiSCH [28]. In the first case, a network manager is responsible to ensure contention-free network access by scheduling transmissions in time slots and deciding the SF and the channel frequency of each transmission in the time slots. Mesh approaches require frequent node inter-communications to maintain routes and schedules, thus, exhibit a high overhead [29]. They are more suitable for duty cycle-free bands such as the LoRa 2.4 GHz and the IEEE802.15.4e.

2.5. Discussion

The main drawback of all time-slotted approaches is the fixed slot size which, in LoRa, is translated to fixed settings in terms of SF, channel bandwidth, and maximum number of transmitted bytes per slot. On one hand, many of the aforementioned approaches select a very high slot size (e.g., SF9, Bandwidth (BW) 125kbps, 250Bytes max payload) in order to accommodate any possible packet size and, thus, support any possible application. However, this approach leads to an extremely high waste of time and energy resources. For example, a node that can reach the gateway with SF7 and has 16Bytes to transmit, needs a roughly 50 ms long timeslot (plus some extra time for overheads and some time to accommodate the clock drift). On the contrary, a time slot with SF9 and 250 Bytes of payload is approximately 1.23 s long. This is translated to 1230−50=1180 ms (or 1.18 s) of wasted time, if transmissions with lower SF and payload size use the same time slots with SF9/250bytes. Moreover, the nodes are obliged to use a higher SF which implies a higher energy consumption. On the other hand, selecting a small slot size based on a shorter packet size requires multiple transmissions per node and additional overhead due to packet fragmentation. A possible solution would be to find a trade-off between the two options, however, the problem of highly wasted resources is not eliminated.

Allowing variable slot sizes requires the transmission of a strict schedule that needs to be communicated to the nodes. As it is mentioned in some studies [23,29], the low data rates of LoRa transceivers and the limited radio duty cycle makes this process a hard and unreliable task.

3. Time-slotted LoRa with variable payload support

Towards addressing the challenges above, the TS-VP-LoRa is proposed aiming to schedule data packet transmissions with variable payload from LoRa nodes to the gateways by utilizing uniquely allocated timeslots. Based on the new scheme, the whole available bandwidth is defined of synchronous uplink and downlink channels. We assume that there are C available channels (e.g., in the EU with TheThingsNetwork (C=8): 868.10 MHz, 868.30 MHz, 868.50 MHz, 867.10 MHz, 867.30 MHz, 867.50 MHz, 867.70 MHz and 867.90 MHz), for the LoRa nodes to send data packets to the gateways. Each of these channels is arranged in units of superframes, which have a specific structure and duration.

The next subsections present the TS-VP-LoRa functionalities in detail. Table 1 helps the reader with the basic notations.

Table 1
Basic notations and their meaning.

Notation	Meaning
SF	Spreading Factor
BW	Bandwidth
C	Radio Channels
T_{super}	Superframe duration
BeW	Beacon Window
PL	Payload range
T_{SF}	Timeslot duration
S	Superframe
k	Number of payload ranges
PLoss	Path Loss
G	Gaussian variable

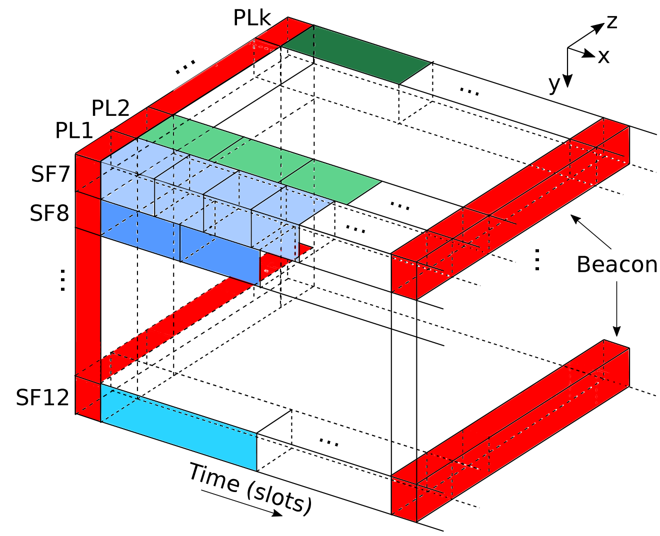

Fig. 1. A collection of superframes spanning different SFs and payload ranges (PL1–k).

3.1. Frame advertisement and timeslot assignment

In TS-VP-LoRa, scheduling is coordinated by the network server via the gateways. The gateways periodically transmit beacons to the LoRa nodes by utilizing one of the available channels. In TS-VP-LoRa, multiple parallel superframes coexist and each of them corresponds to a payload range and SF combination. The number of co-existing frames depends on the number of available channels C. More details are given in the next subsection. The network server is responsible for assigning a unique timeslot to each LoRa node that requests to join its network. The process is similar to the one described in [9]. This assignment is initiated via the join request, upon which the network server selects a timeslot for each node. After that, a node can calculate the slot number via the device address (DevAddr) which is included in the join-accept packet [9]. The same assigned timeslot number will be utilized in all superframes to be received by the node regardless the payload range frame.

3.2. Superframes and beacons

In TS-VP-LoRa, the system consists of virtual superframe structures just as the ones defined in [30]. Based on this study, each superframe lasts for T_{super} seconds and it is initiated by a beacon. In a superframe, the beacon is followed by a Beacon Window (BeW), defined as the interval between two successive beacons. As it is depicted in Fig. 1, there can be up to 6xk parallel virtual superframes for all 6 SFs and k distinct payload ranges.

In TS-PS-LoRa, each BeW consists of a specific number of timeslots. Each timeslot lasts T_{SF}^{k} seconds, which is defined based on the size of

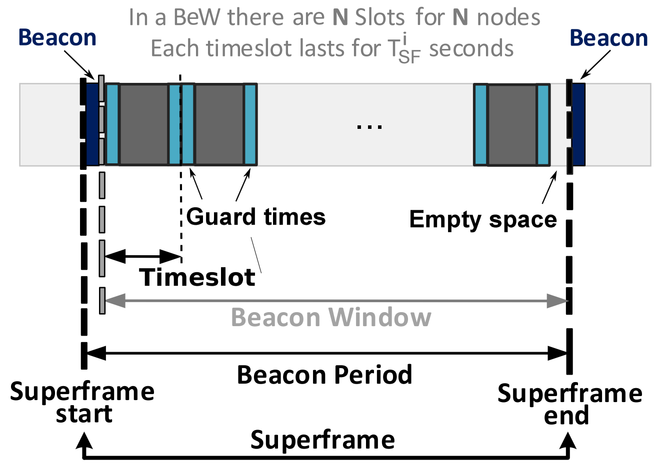

Fig. 2. Structure of a superframe for payload range i in the TS-VP-LoRa scheme.

the packet to be transmitted (by selecting the appropriate range), as well as the selected SF value. Each timeslot encapsulates two fixed-sized guard time intervals g to tolerate slight desynchronizations. The guard time size depends on the crystal oscillator drift time and the beacon window size. The structure of a superframe is illustrated in Fig. 2. The number of slots accommodated in each superframe depends on the timeslot size which in turn depends on the SF and the payload size. Apparently, less timeslots are accommodated in frames of higher SF and higher payload size. Assuming that each superframe has a size equal to T_{super} seconds and each slot is T_{SF} seconds long, then $\lfloor T_{super}/T_{SF} \rfloor$ slots can fit in the frame. Based on this fact, empty space may exist at the end of the frame if the slot size does not divide evenly the beacon window size. In particular, T_{super} - $\lfloor T_{super}/T_{SF} \rfloor$ is the maximum gap that may exist at the end of the superframe.

As demonstated in Fig. 3, a beacon has 6 Bytes length and consists of the following fields which help end-devices to schedule their transmissions by utilizing the appropriate frequency channel. In the first 3-bit field, *Packet Type*, the type of the respective packet is provided. The Network ID follows with 3 bits and the superframe ID with 32 bits. The number of payload ranges k consists of 3 bits, the same for the number of available channels C. A 4-bit number which represents the payload length in bytes is finally added. It must be noted that the nodes can find the actual payload ranges in bytes by equally dividing the max LoRa payload size + 1 (i.e., 255+1) by k. The list of available channels is known through the OTAA registration. However, the gateway may change the value of C to adjust the channel hopping sequence.

3.3. LoRa nodes scheduling

In TS-VP-LoRa, the nodes can register to the network at any time by sending a join-request message to the gateway (similar to LoRaWAN). Once they register, the nodes receive valuable scheduling information from the gateway by listening to the broadcasted beacons. As with the typical LoRaWAN, each node initially selects a random channel (of the 3 mandatory) to transmit the join-request to the gateway, while the SF value is selected based on the most energy-efficient and reliable value.

In order to send a data packet to the gateway, the node must decide the payload size and the channel of transmission, while also being aware of the duty cycle restrictions. The nodes can transmit a packet size of up to 235 bytes (maximum payload at 222 bytes with 13 bytes overhead), which is selected before each transmission. One of the main objectives of the scheduling scheme is to reduce the number of collisions that could occur due to the variety of transmissions with different payload sizes but on the same SFs. To achieve this goal, a fair channel scheduling and hopping mechanism is proposed where transmissions that belong to different payload ranges are scheduled on different radio channels. In this way, intra-SF collisions are avoided while inter-SF collisions may occur only if two or more nodes transmit on the same payload range, on different SF, and on an overlapped timeslot. Moreover, the channel assigned to each payload range changes at each superframe n using a channel hopping formula as presented in the following equation:

$$Ch_n = (S_n + PL_n) \ \% \ (C - 1), \tag{1}$$

where S_n is the current superframe id, PL_n depicts the number of the payload range chosen for this transmission ($PL_n \in [0..k-1]$), while k refers to the maximum number of ranges that can be supported ($k \leq C, C \geq 3$). By utilizing Eq. (1), a cyclic generator assigns the next transmission channel to each node, distributing efficiently the network load in each channel.

4. LoRa MAC schemes implementation

In order to assess the benefits of TS-VP-LoRa scheduling, a comparison is provided between the proposed scheme, the FCA-LoRa scheduling method [30], the legacy LoRaWAN utilizing pure Aloha, and LoRaWAN operating on Slotted-Aloha. For the implementation of all four schemes, the nodes are instructed to produce and transmit data packets with variable payloads to a single gateway and follow the duty cycle restrictions. An important fact to be stated is that no acknowledgements are scheduled to be sent in these deployments to verify the successful reception of a data packet from the gateway. While legacy LoRaWAN allows each end-device to randomly transmit their data, FCA-LoRa leverages beacons frames broadcasted by the gateway in order to synchronize the LoRa nodes and avoid collisions. In addition, it adopts the CSMA/CA model to handle channel access and allows dynamic SF allocation in transmissions within a superframe. On the other hand, the Slotted-Aloha method defines the division of the channel time into slots with fixed duration. Each node selects a slot and transmits a packet at the beginning of that slot. An important rule applied in all four schemes is that if two or more end-devices transmit their packets during the same period, a collision may occur; otherwise, no collision is generated, and the data are properly transmitted. Intra- and inter-SF collisions as well as the capture effect are taken into account [5].

TS-VP-LoRa, FCA-LoRa, legacy LoRaWAN, and Slotted-Aloha LoRaWAN were developed in OMNeT++ [31] discrete event simulator by using the FLoRa (Framework for LoRa) simulation tool [32] and the INET framework, an open-source OMNeT++ model suite for wired, wireless and mobile networks. FLoRa is an open source tool implementing various modules of the LoRaWAN network, including the LoRa physical layer and the legacy LoRaWAN MAC protocol operations. Furthermore, FLoRa provides a module to evaluate the energy consumption of end-devices.

In order to implement the four aforementioned schemes, a common LoRaWAN network topology was defined including a Network Server, an Internet Cloud entity, a gateway, and multiple end-devices. The Network Server utilizes an application in order to send and receive information from the gateway via TCP/IP connection. The gateway is responsible for receiving data frames from the end-devices, as well as forwarding this information to and from the Network Server. As it is also done Class-B LoRaWAN, the gateway (or a separate gateway) has the ability to broadcast beacon frames to the nodes for synchronization purposes. Each end-device includes a LoRa transponder for signal transmissions and an energy consumption module, which is responsible for monitoring the end-device's current consumption, the remaining battery lifetime, as well as the energy efficiency of data delivery.

Each end-device turns its radio on to transmit a data packet or receive a beacon. At the end of every reception or transmission, it turns off its transceiver. The LoRa nodes' energy consumption modules measure energy consumption by monitoring the variations performed in each particular radio state. Regarding transmissions, energy consumption is mainly based on the employed transmission power of each

Field	Packet Type	Network ID	Superframe ID	PL ranges (k)	Channels (C)	Packet Length
Length (bits)	3	3	32	3	3	4

Fig. 3. Structure of beacons in the TS-VP-LoRa scheme.

Table 2
European regional parameters for LoRaWAN.

Parameter	Value
Bandwidth	125 kHz
Frequency	863–870 MHz
Spreading Factor	7 to 12
Duty Cycle	≤1%
Bit Rate	0.3–5 kbps
Transmission power	2 to 14 dBm

node [33]. The definition of the transmission power levels was based on [34], while the definitions of supply voltage at 3.3 V and the drawn current in the receive and idle modes were based on the Semtech SX1272/73 datasheet [35].

4.1. Physical layer specifications

As it is explained in Section 1, the physical layer of LoRa employs a spread spectrum modulation technique to encode information. In particular, it defines the encoding of each symbol with 2^{SF} chirps, where SF takes a value between 7 to 12. Higher values of SF result in a longer transmission time for each symbol and hence a longer communication range. The bandwidth defines the chirp rate in LoRa communications, since the chirp rate is equal to one chirp per second per Hertz of bandwidth [36]. The deployments of TS-VP-LoRa, FCA-LoRa, legacy LoRaWAN and Slotted-Aloha LoRaWAN are based on the European LoRaWAN specification, as presented in Table 2, utilizing the 863–870MHz ISM band, a channel bandwidth of 125 KHz, and a less than one percent duty cycle per spectrum band. The duty-cycle restriction refers to the amount of time that an end-device needs to wait before the next data transmission.

Moreover, the deployment of the LoRa PHY layer modules necessitates the definition of a mechanism that replicates the losses caused by signal attenuation and shadowing during data transmissions. It is a fact that signal receptions depend on the reception power, the transmission power, and the sensitivity of the receiver. Due to this fact, the path-loss model with shadowing is utilized in TS-VP-LoRa, FCA-LoRa, legacy LoRaWAN and Slotted-Aloha LoRaWAN to simulate this effect for long distances [37]. Based on this model, path-loss is calculated as follows:

$$PLoss(d) = \overline{PLoss(d_0)} + 10alog(\frac{d}{d_0}) + G \quad (2)$$

where d is the distance between the transmitter and the receiver, $PLoss(d_0)$ is the mean path-loss for d_0, a is the path loss exponent, and G is a zero-mean Gaussian distributed random variable with standard deviation.

4.2. MAC layer specifications

4.2.1. Aloha-based MAC layer

According to the legacy LoRaWAN, end-devices can communicate with the gateway by utilizing an Aloha-based MAC protocol to access the wireless medium [38]. Based on this scheme, LoRa nodes can transmit data to the gateway whenever they choose. During the preparation of an uplink unconfirmed transmission an end-device selects randomly a frequency channel and defines the payload size of the packet to be transmitted. Only if the duty cycle restrictions are satisfied, the transmission is initiated. The SF value is selected according to distance between the node and the gateway, similarly to Adaptive Data Rate (ADR) [39].

4.2.2. Slotted-Aloha-based MAC layer

By utilizing the Slotted-Aloha scheme, LoRa nodes can transmit information to the gateway in a scheduled and controlled manner that theoretically decreases the chance of packet collisions [15]. Based on this scheme, the time between two successive synchronizations (i.e., beacon receptions) is divided into a specific number of timeslots. In Slotted-Aloha each timeslot is calculated by utilizing SF11 and 80 bytes so that most of the possible transmissions can fit into a single timeslot, without wasting many channel resources. For each transmission, the timeslot number is selected randomly. Each end-device is allowed to transmit after a channel is randomly selected for the upcoming transmission. The payload size is also randomly selected. Nevertheless, the SF value remains predefined and selected according to distance between the node and the gateway. Last but not least, only if the duty cycle restrictions are satisfied, a transmission is initiated in the corresponding timeslot. Otherwise, the node postpones the transmission for the next round.

4.2.3. FCA-LoRa MAC layer

The basic principle of FCA-LoRa [30] is that the gateway handles effectively up-link transmissions via broadcasting beacon frames to the end-devices. The time is divided in superframes over all available frequency channels. Each superframe is initiated with a beacon frame. Based on this scheme, the nodes remain inactive until the reception of the first beacon frame from the gateway. The gateway broadcasts beacons periodically in all frequency channels, as soon as it receives the launching command from the Network Server. Once a node receives a beacon, it schedules an uplink transmission at a random time offset, which is strictly based on the time interval set by the duty cycle restrictions. Then, the packet is transmitted in the channel in which the beacon was received. In FCA-LoRa, end-devices can transmit more than one times in the same superframe (without violating the average packet rate). In order to avoid packet collisions and increase reliability and fairness, FCA-LoRa utilizes the CSMA/CA method to gain access to chosen frequency channel. The CSMA/CA mechanism maintains a contention window that defines the number of specific time periods that need to be clear of channel activity before the transmission can commence.

4.2.4. TS-vp-lora MAC layer

The TS-VP-LoRa MAC layer, in order to schedule future data transmissions, each end-device must first send a request to join the gateway utilizing the communication parameters extracted from the beacon frames. Until the reception of the first beacon, the end-devices are in receiving mode. The join-request has a two-fold purpose for the LoRa node. Once the join-request reaches the gateway, a downlink message will be sent to acknowledge the end-device as a new member in the network and assign it to a unique timeslot for data transmissions. The gateway keeps a registry with the assigned timeslots during each simulation and forwards all data to the Network Server. The slots are given serially until the maximum number of slots is reached, which is defined by the minimum payload range and the minimum SF (e.g., ∼1300 slots with the current simulation settings). The number of slots may span multiple frames for higher SFs and payload ranges. In TS-VP-LoRa, end-devices schedule data transmissions not only based on the randomly selected payload size and the assigned SF values, but also by considering the previously utilized frequency channel. Each node has its unique timeslot in each superframe period as it assigned during the registration. As it is described in Section 3, this arms end-devices

Table 3
Simulation parameters.

Parameter	Value
Simulation time	2 days
Deployment area	1500 × 1500 m
Number of gateways	1
Channel bandwidth	125 kHz
Radio Channels (C)	8
Data SF value	7 to 12
Beacon SF value	12
Duty Cycle	≤1%
Code rate	4/5
Max transmission power	14 dBm
Packet size	23 to 235 bytes
Avg packet rate	2 min
Beacon Window	128 s

Table 4
TS-VP-LoRa payload ranges.

Range #	SF values allowed	Packet size (including overhead)
$LP1$	7 to 12	up to 32 bytes
$LP2$	7 to 9	up to 64 bytes
$LP3$	7 to 9	up to 96 bytes
$LP4$	7 to 8	up to 128 bytes
$LP5$	7 to 8	up to 160 bytes
$LP6$	7 to 8	up to 192 bytes
$LP7$	7 to 8	up to 224 bytes
$LP8$	7 to 8	up to 235 bytes

with the ability to avoid packets collisions and fairly distribute the variable payloads in the available frequency channels while minimizing latency. Each node keeps track of its transmissions and according communication parameters in the MAC layer. In order to determine the size of the timeslot for each transmission, an almost zero computation effort is required by the nodes. The only calculation the nodes need to do is to find out the timing they will wake up to perform the transmission. For a given timeslot number by the network server, the wake up time of the node is calculated by multiplying the timeslot number with the appointed timeslot duration for the selected payload range.

5. Evaluation & discussion of the results

This section focuses on the evaluation of TS-VP-LoRa by comparing it against FCA-LoRa, legacy LoRaWAN and Slotted-Aloha LoRaWAN schemes using OMNeT++ [32].

5.1. Setup

The simulation scenario defines a deployment area of 1500 × 1500 meters using variable number of randomly positioned nodes and a single gateway. The gateway is located at the centre of the area, maintaining an Ethernet connection with a Packet Forwarder entity, a single Network Server and the Internet Cloud. For the implementation of the ideal back-haul network, the INET framework was utilized employing zero packet loss and a transmission delay of 10 ms. Every end-device is assigned to a specific SF value based on its distance from the gateway and it is instructed to transmit unconfirmed data packets to the gateway. Each node utilizes a maximum initial transmission power at 14dBm, with a code rate set to 4/5 and channel bandwidth at 125 kHz. Furthermore, all four approaches utilize the European regional parameters for the LoRa physical layer, following a less than or equal to one percent duty cycle specification. Table 3 summarizes the configuration parameters for all algorithms. Finally, all nodes randomly generate a data packet between 19 and 222 bytes (+13 bytes overhead) and choose the minimum possible payload range from Table 4. For fair comparison purposes, we chose all four schemes to follow the LoRaWAN maximum payload size (without overhead) which is 222, 222, 115, 51, 51, and 51 bytes for SF7 to SF12, respectively. Based on this, the selected TS-VP-LoRa payload ranges are presented in Table 4.

Each approach is evaluated based on a variety of nodes from 100 to 500 in steps of 100 nodes. Each experiment lasted for 2 days, equally to 172,800 secs of simulated time. For the Legacy LoRaWAN and Slotted-Aloha LoRaWAN schemes, the simulation is initiated by the nodes, which become active in a random time offset in order to transmit a request to the gateway. In both of these schemes, uplink packet transmissions occur randomly with a mean of 2 min. On the other hand, in TS-VP-LoRa and FCA-LoRa, the simulation is initiated by the Network Server, which gives permission to the gateway to start broadcasting beacons in the network. In these two schemes, node transmissions are initiated only after the reception of a beacon from the gateway. In TS-VP-LoRa, uplink packet transmissions are scheduled only at the beginning of each timeslot. In FCA-LoRa, a random time offset is calculated by considering the payload size and duty cycle restrictions, to increase the successful uplink packet transmissions to the gateway.

The evaluation of the approaches was focused on the following performance metrics: (a) throughput, measured as the number of messages correctly received by the gateway divided by the total number of messages sent by the end nodes, (b) total number of collisions that occurred at the gateway, (c) total number of packets sent to the gateway, (d) mean energy consumption from all the nodes in the network, (e) average latency for variable number of end-devices and (f) channel utilization based on uplink transmissions from all the end-devices.

5.2. Results

Fig. 4 verifies the superiority of TS-VP-LoRa scheduling method by significantly decreasing packet collisions in the LoRa Gateway receiver in contrast to legacy LoRaWAN, FCA-LoRa and Slotted-Aloha LoRaWAN scheduling methods. Due to the unique channel association with the payload ranges, intra-SF collisions are absent. All the collisions that happen are due to the imperfect orthogonality of SFs. As expected, the highest collision number is displayed by FCA-LoRa. Despite the CSMA mechanism, this result is due to the fact that all nodes aim to achieve a maximum number of variable payload transmissions in a restricted period of time (between two beacons) and based on a completely random channel distribution. Following the principles of this scheme, a large number of nodes with the same SF value may utilize the same channels for transmissions. Furthermore, based on the basic principles of the Aloha protocol scheme, it is quite possible for two or more end-devices to attempt to communicate with the gateway, at the same time. In such a case, if both end-devices use the same channel and also modulate their data with the same SF, interference will be caused, leading to packet collision. The employment of Slotted-Aloha scheme could help eliminate partial collisions, since it utilizes timeslots for data transmission. However, access in the medium remains uncontrolled. The occurrence of a collision depends on the decision of more than one end-devices to transmit a packet simultaneously [40]. The lack of coordination in packet transmissions but also the long slot length that has been selected in Slotted-Aloha contribute to a poor performance is caused for both pure and slotted Aloha in LoRaWAN.

Regarding the throughput, Figs. 5 and 6 present a high and stable performance of the TS-VP-LoRa scheduling method despite the scaling up of the number of end-devices and some inter-SF collisions that may happen. As the number of the nodes in the network increases, FCA-LoRa displays the second best performance in terms of throughput, due to the utilization of the CSMA-CA mechanism. Then, follows the Slotted-Aloha LoRaWAN scheme, while in the last place the legacy LoRaWAN scheduling scheme displays a slightly worse performance. It is obvious that TS-VP-LoRa favours successful packet transmissions and receptions in contrast to the other schemes. This asset originates

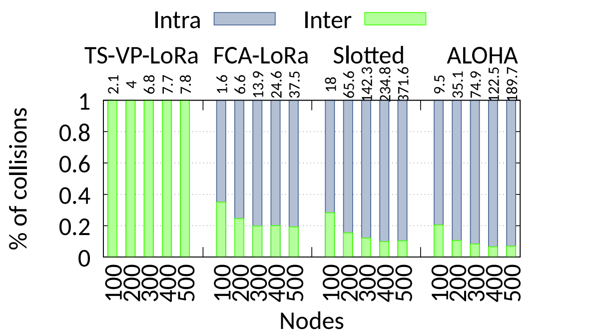

Fig. 4. Percentage of Intra- and Inter-SF collisions for variable number of end-devices. The number on top of the bars represents the absolute number of total collisions in thousands.

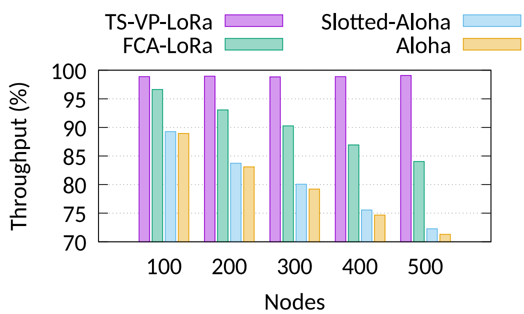

Fig. 5. Throughput (Packet Reception Ratio) for variable node scenarios.

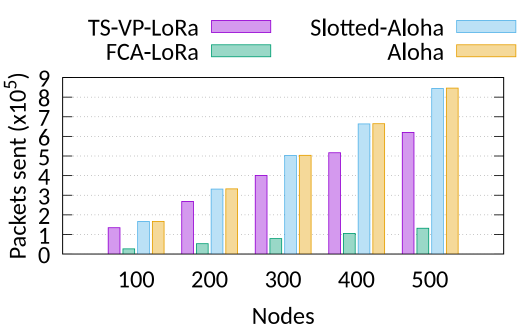

Fig. 6. Total packets sent to the Network Server for variable number of end-devices.

from TS-VP-LoRa's ability to consider the variable payload sizes and schedule each uplink transmission accordingly, facilitating channel and node fairness in the network. It is also evident, that legacy LoRaWAN and Slotted-Aloha LoRaWAN manage to produce and transmit a greater amount of packets than FCA-LoRa scheme. In FCA-LoRa, beacons are broadcasted periodically in frequency channels. Each beacon is sent in one channel at a time, in a sequential manner. Due to this fact, it is highly unlikely to achieve a high number of transmissions with variable payloads. However, legacy LoRaWAN and Slotted-Aloha LoRaWAN do not manage to achieve a higher percentage of successful transmissions than FCA-LoRa. This result is basically due to the randomization factor in packet size selection and frequency channel selection.

Channel fairness for TS-VP-LoRa scheme is evident in Fig. 8, while Fig. 7 demonstrates that all four scheduling methods maintain stable channel utilization values in all simulation scenarios, despite the scaling of the network to a larger number of LoRa end-devices. Channel utilization is referred to the average number of times each of the eight frequency channels was utilized for a transmission from all the end-devices in the network. The simulation results display a significant increase in the case of TS-VP-LoRa scheme.

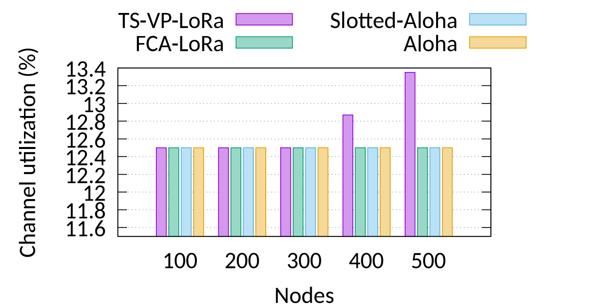

Fig. 7. Accumulative channel utilization percentage for variable number of end-devices.

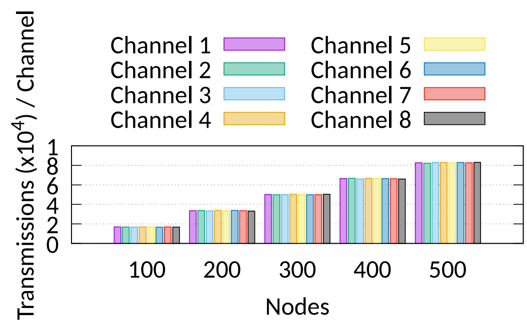

Fig. 8. Total transmissions per radio channel in TS-VP-LoRa.

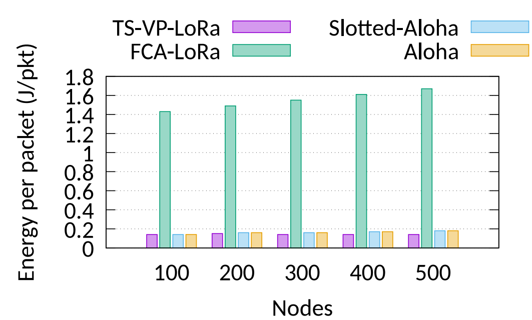

Fig. 9. Mean energy consumption per packet for variable number of end-devices.

Furthermore, regarding the evaluation of energy consumption, TS-VP-LoRa seems to be favoured in contrast to the other scheduling methods despite the increase of end-devices in the network. As depicted in Fig. 9, FCA-LoRa nodes consume more energy, since they are forced to remain active for most of the simulation time, so as to achieve a maximum number of transmissions in the duration of each superframe. It is also evident that the mean energy consumption in TS-VP-LoRa remains stable as the network scales. On the other hand, Slotted-Aloha LoRaWAN as well as legacy Aloha LoRaWAN scheduling methods have a smaller average energy consumption due to the rule of enabling LoRa end-devices' activation for a fixed amount of time and the absence of the need to listen for beacons. TS-VP-LoRa manages to get the best of the choices above towards scaling up LoRa networks; since it enables the maximum number of successful transmissions by maintaining a relatively low energy consumption.

Last but not least, Fig. 10 demonstrates a significant advantage of the TS-VP-LoRa scheme. Latency is considered an important parameter of IoT applications. This parameter is defined and calculated as the interval time between the production of a data packet in a node and its reception by the LoRa Gateway. The TS-VP-LoRa scheme has proven to achieve the minimum latency in comparison to the other three scheduling schemes, enabling faster and successful packet transmissions despite the variable payload size.

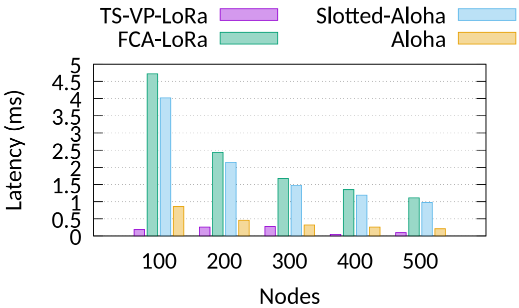

Fig. 10. Average latency for variable number of end-devices.

To sum up, TS-VP-LoRa has proven to be more efficient, reliable and energy conservative in contrast to FCA-LoRa, legacy LoRaWAN and Slotted-Aloha LoRaWAN schemes for supporting variable payload. Taking under consideration, the randomness factor in simulation scenarios, the evaluation of TS-VP-LoRa is favourable in terms of throughput and energy consumption, enabling a greater number of produced packets to be received successfully by the Network Server, maintaining high channel utilization despite the number of LoRa end-devices and eliminating collisions.

6. Conclusion & future work

LoRaWAN is a rapidly evolving technology with the potential of supporting a large number of IoT applications. It is a fact that the deployment of modern applications require a variety of challenges to be faced, ranging from an increasing number of payloads to network interoperability issues. In this work, we presented, implemented, and evaluated TS-VP-LoRa, a novel Time-Slotted LoRa MAC scheme aiming to efficiently support variable payloads in LoRa wide-area networks while minimizing the number of collisions. This novel scheduling process proved that is able to handle efficiently ranging LoRa network traffic in both frequency and payload size in the case of a single LoRa gateway scenario. Future work includes the deployment of TS-VP-LoRa in multiple gateway scenarios, as well as in specific IoT applications.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Panagiots Sarigiannidis reports financial support and equipment, drugs, or supplies were provided by Horizon 2020.

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