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Multiple Access in Large-Scale LoRaWAN: Challenges, Solutions, and Future Perspectives

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***Abstract*—Enabling energy-efficient and long-distance wireless networking is expected by various Internet-of-Things systems and consumer electronics applications. Low Power Wide Area Networks can commendably satisfy this requirement because of their combination of low-power and long-range features. Thereinto, open-standard Long Range Wide Area Network (LoRaWAN) is the representative player with hundreds of deployment cases worldwide. Unfortunately, current multiple access (MA) strategy for LoRaWAN has been proved to incur severe wireless signal interference under large-scale deployment. This is the inherent hindrance for current LoRaWAN to support large-scale wireless networking. In this context, this article aims to provide a detailed tutorial of MA issues in large-scale LoRaWAN for the first time. We start with several practical use cases of large-scale LoRaWAN. We then explain the detailed challenges of large-scale LoRaWAN networking. Representative MA solutions for better LoRaWAN networking are then described and compared. Future research directions for enhanced MA protocol design are also discussed.**

LOW POWER WIDE AREA NETWORKS (LPWANs) have flourished in the past few years as an emerging and promising networking paradigm for diverse Internet-of-Things (IoT) and consumer devices to connect with the Internet [1]. This is because LPWANs enable low-power (milliwatts) and long-range (several kilometers) wireless networking with decent data rate (kilobits per second). Specifically, Long Range Wide Area Network (LoRaWAN), as one of the representative LPWAN technologies, is drawing extensive

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interest in recent years. It typically adopts a three-layer network architecture. The bottom layer contains a number of end devices for information provision. Gateways are at the middle layer for data exchange with the end devices. At the top layer is back-end network and application servers for data management. LoRaWAN has been implemented in more than 170 countries for sensing of solar power plants, waste management, power usage monitoring, and so forth.

Despite the deployments of LoRaWAN in practice, it is still barely satisfactory to employ LoRaWAN for large-scale IoT networking. In a large-scale LoRaWAN, massive (*e.g.,* hundreds of) end devices are typically distributed for asset tracking, humidity monitoring, and so forth. Particularly, the end devices usually coexist in the same frequency band and their transmissions severely interfere with each other [2]. This is due largely to the use of ALOHA protocol for multiple access (MA) support among end devices. This protocol allows each end device to occupy a channel whenever it has data to send. According to [3], the theoretical maximum capacity of an ALOHA network is merely 18% of the maximum in the optimal case.

In this context, the past three years have witnessed the ever-increasing proposals of better MA techniques for large-scale LoRaWAN. Their main goal is to reduce signal interference as much as possible by coordinating the behaviors of wireless channel access and signal transmissions among coexisting end devices. This coordination can be centralized at gateways or distributed at end devices. Generally, the proposed solutions migrate conventional MA protocols to LoRaWAN or develop new MA strategies based on LoRaWAN architecture. Receiving tremendous attention with both academic research results and industrial applications, this topic has been believed as the key for LoRaWAN to evolve as a mature wireless networking technology.

Accordingly, this article aims to provide a deep overview of MA issues in large-scale LoRaWAN. While several existing LoRaWAN networking surveys also mention the aspects of MA, they target a wide range of issues (*e.g.,* physical layer, link layer, application layer, and performance metrics) in LoRaWAN and thus their description of the MA issues appears to be limited to only a brief summary of several selected MA proposals in the literature [4]–[8]. In this work, however, we specifically focus on more details of MA in LoRaWAN by (i) providing several practical use cases of LoRaWAN to show how current LoRaWAN is insufficient for large-scale IoT networking, (ii) explaining why LoRaWAN fails to withstand massive interfering links, (iii) deeply analyzing the up-to-date and representative LoRaWAN MA proposals in the literature with detailed categorization, explanation, and performance comparison, and (iv) discussing several future research insights regarding LoRaWAN MA to facilitate large-scale LoRaWAN networking.

LoRaWAN Deployments in Practice

In order to show the deficiency of LoRaWAN networking under large-scale deployment, we demonstrate and analyze several use cases of large-scale LoRaWAN in practice. Note that according to our survey, there are many available documents regarding various use cases of LoRaWAN. However, they do not target large-scale deployment or merely provide high-level description of the targeted applications while keeping the corresponding networking details secret, which makes it impossible to investigate the drawbacks of large-scale LoRaWAN networking. In this context, our selection of the use cases is based on a limited number of appropriate articles that describe both the network settings of large-scale LoRaWAN and the corresponding experiment results. Among them, the following three include the most details that are helpful for us to explain how the real-world LoRaWAN is insufficient for large-scale IoT networking.

Electricity Metering in a Rural Area

LoRaWAN Setup: Gehrden is a typical smaller city of Germany mainly with low buildings and detached houses. In this area, an outdoor LoRaWAN has been deployed to measure and manage the amount of electric energy consumed by the included households [9]. As shown in Figure 1 (a), this is achieved by installing seven LoRaWAN gateways each of which operates on eight channels and 536 LoRaWAN-enabled electricity meters as the end devices. Each end device is configured to send a 17-byte packet every 15 minutes. A backbone network server adaptively optimizes the data rates of the end devices based on the strongest signal received by at least one gateway.

Networking Problems: In this context, it is observed that there exist six types of data rates (*i.e.,* DR0-DR5) with the distribution of 17%, 11%, 12%, 7%, 7%, and 46% across all end devices in the network [9]. Moreover, the 17-byte packet under DR0-DR5 has the time-on-air of 1319 ms, 660 ms, 330 ms, 165 ms, 93 ms, and 52 ms, respectively. Thus, given that the

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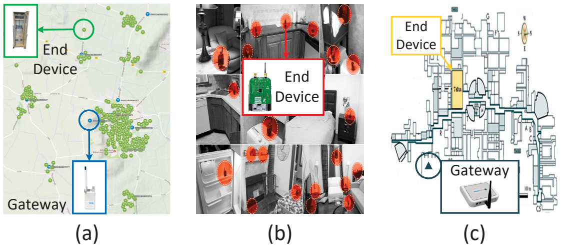

Figure 1. Practical deployments of LoRaWAN in (a) Gehrden, Germany [9], (b) Philadelphia, USA [10], and (c) University of Oulu, Finland [11].

transmission interval of end devices is 15 minutes, we can estimate the load of each of the eight channels as $536 \times (0.17 \times 1.319 + 0.11 \times 0.66 + 0.12 \times 0.33 + 0.07 \times 0.165 + 0.07 \times 0.093 + 0.46 \times 0.052) \div (15 \times 60) \div 8 \times 100\% = 3\%$. According to [9], the resulting packet loss rate due to the interference between wireless links is approximately 6% given that all packets are received by a single gateway. Worse still, if the originally planned 7000 electricity meters are all deployed ultimately and operate in this way, the channel load will be close to 40%, leading to the packet loss rate of 60%. This will incur severe network connection breakdown due to the coexistence of massive interfering links.

Full-Scale Network Emulation in an Urban Area

LoRaWAN Setup: To evaluate the ability of LoRaWAN for IoT networking in dense urban environments, machineQ and Semtech deployed an enterprise-grade LoRaWAN in Philadelphia, USA [10]. It consisted of ten eight-channel gateways and 100 end devices in total. Particularly, most of the end devices were deployed in residences with varying degrees of signal path loss as shown in Figure 1 (b). To emulate a full-scale LoRaWAN with 10000 end devices installed, each of the 100 end devices transmitted at a certain packet rate so that the same amount of traffic as 10000 end devices can be achieved. Specifically, the experiment targeted three phases with different amounts of traffic: Phases 1, 2, and 3 with 250000, 500000, and 1000000 packets per day, respectively. Accordingly, the adopted packet rates of the end devices were 104, 209, and 417 packets per hour in Phases 1, 2, and 3, respectively. The packets were transmitted with randomized intervals.

Networking Problems: The data rates of the end devices are determined based on their indoor locations and proximity to the gateways. Specifically, four types of data rates (*i.e.,* DR0-DR3) are allocated to the end devices and the percentage of end devices per data rate is 13%, 26%, 27%, and 34% for DR0-DR3, respectively [10]. In other words, the numbers of end devices adopting the data rates in this experiment are 13 with DR0, 26 with DR1, 27 with DR2, and 34 with DR3. In this context, the study result in [10] shows that in Phase 3, the averaged signal overlapping ratio under each data rate can reach 10%, 11%, 6%, and 4% for DR0-DR3, respectively. While the signal overlapping ratios are not in a very high level at first sight, it does not mean that LoRaWAN networking is robust under large-scale deployment. This is because each data rate in this experiment is adopted only by a handful of end devices and thus the number of interfering links is too small to mimic a large-scale LoRaWAN. Given that the signal overlapping ratio under each date rate increases approximately in a logarithmic manner from Phase 1 to Phase 3 as illustrated in [10], we can predict that it will be 70%-80% when 1000 end devices are deployed and operate as Phase 3.

Environmental Monitoring in a University

LoRaWAN Setup: As the emergence of the Smart Campus concept, an indoor LoRaWAN has been deployed in University of Oulu, Finland to facilitate the collection of versatile data related to surrounding environments [11]. It distributes 331 LoRaWAN end devices capable of sensing different environmental parameters (*e.g.,* temperature, humidity, and CO_2 levels) in an indoor area as shown in Figure 1 (c). A single gateway operating on three channels is employed to collect the data. A fixed data rate with the shortest packet time-on-air is configured at all the end devices and does not change in the study. The transmission interval of the end devices is set to be 15 minutes.

Networking Problems: Based on the network settings above, the channel load in this network is 2%-3%. Despite the low level of the channel load, the observed packet error rate is 27% on average over a long period of time [11]. This means that in a data collection period with the duration of 15 minutes, more than 25% end devices cannot successfully send their sensing data to the gateway, which can lead to severe environmental monitoring errors and faults. Worse still, this result is obtained under the data rate with the lowest signal interference probability. As a result, given a practical LoRaWAN where different data rates are used and

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much more interfering links exist, the packet error rate will increase rapidly and reach a much larger value.

Networking Challenges in LoRaWAN

Given the problems in the LoRaWAN use cases above, we deeply analyze the underlying reasons that make LoRaWAN networking challenging under large-scale deployment from the perspectives of both LoRaWAN physical layer (PHY) and medium access control layer (MAC).

LoRaWAN Networking Primer

In LoRaWAN PHY, the used modulation scheme is called chirp spread spectrum (CSS). CSS splits a LoRaWAN signal into multiple pieces with the same duration. Each piece is called a chirp whose frequency increases linearly with time. LoRaWAN calculates the increment step of the frequency with a parameter called spreading factor (SF). SF also determines the duration and the contained number of bits of each chirp. LoRaWAN demodulates a signal by multiplying each chirp with a reference signal and applying Discrete Fourier transform (DFT) thereafter. This will yield a peak DFT bin that corresponds to the carried data of the chirp. In particular, even when two LoRa signals with different SFs applied interfere with each other, this type of demodulation scheme can in most cases clearly recognize the DFT bins that indicate the transmitted data in the two signals. We call this feature as inter-SF orthogonality.

In LoRaWAN MAC, a simple and lightweight channel access protocol, ALOHA, is basically adopted [3]. It performs a “send-as-you-want” type of MA operation for all involved end devices. Typically, a LoRaWAN gateway is implemented with multiple (*e.g.,* eight) signal demodulators and hence can receive signals at multiple channels simultaneously. Given a set of available channels, LoRaWAN allows end devices to access the channels in a hybrid mode where a frequency hopping technique is used in addition to ALOHA for signal interference avoidance. Besides, an end device may choose to receive an acknowledgement packet or not based on the reliability requirements of target applications. For the ones that need to be acknowledged, they open one or two receive windows (RX1 and RX2) for acknowledgement packet reception after completing their uplink transmissions [12].

In addition, an important networking feature of LoRaWAN is that for improving the battery life of end devices and maximizing network capacity, a network can control the data rate of the end devices through MAC commands. This is referred to as Adaptive Data Rate (ADR) [12]. With ADR enabled, the transmission parameters of end devices including SF, bandwidth, coding rate, and transmission power can change based on wireless link budget. A notable benefit achieved via ADR is that LoRaWAN signals transmitted using different SFs can be decoded concurrently due to the inter-SF orthogonality.

MA Insufficiency for Large-Scale LoRaWAN

While frequency hopping and ADR are allowed to be used in LoRaWAN networking, the resulting performance improvement particularly under large-scale network deployment is still limited. This is mainly because large-scale LoRaWAN typically involves a great quantity (*e.g.,* hundreds) of end devices randomly distributed in an area. In this context, the available channels at a gateway for frequency hopping cannot afford the massive transmissions from the end devices. Since ADR generally allocates SFs to end devices based on their distances to a gateway, the signals transmitted with different SFs may have huge power differences, which leads to the failure of the inter-SF orthogonality as presented in [13]. Worse still, if a LoRaWAN includes mobile end devices, ADR does not work well since it is basically designed for stable wireless channel environments.

The key reason behind the poor networking performance of LoRaWAN is the use of the ALOHA protocol for MA support. To be more specific, the timing and duration for channel access in ALOHA are determined completely by distributed end devices. End devices do not perform any distributed or centralized operation for clock synchronization and transmission coordination. Obviously, in a large-scale LoRaWAN with a large number of coexisting end devices, this will result in tremendous interfering wireless links and even network connection breakdown. Since ALOHA does not define specific timing references regarding the channel usage, signal interference may occur from the middle of signals with unpredictable starting positions, which further increases the difficulty of signal interference resolution. Besides, ALOHA does not recognize the specific positions of erroneous bits of a corrupt packet. Thus, the same packet needs to be retransmitted in its entirety even when only a minority of bits are corrupted, which increases the probability of the retransmission interfering with other transmissions.

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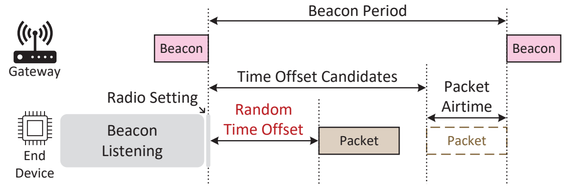

Figure 2. Enhanced ALOHA proposal: RS-LoRa.

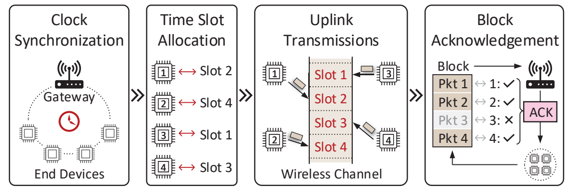

Figure 3. Overview of time-domain channel segmentation-based MA. Pkt: Packet; ACK: Acknowledgement.

Existing MA Solutions for LoRaWAN

Regarding the deficiency of the ALOHA protocol, both academia researchers and networking solution providers have been conceiving MA proposals to enable more harmonious channel access behaviors of end devices. Regarding a limited number of related techniques in the literature, we categorize them into several classes and describe the most up-to-date and representative ones. While the design of better frequency hopping and/or ADR algorithms can also improve the LoRaWAN networking performance, the related technique review is beyond the scope of this article since the core challenge of large-scale LoRaWAN networking lies in the ALOHA-based channel access behaviors of end devices.

Enhanced ALOHA

Instead of changing the core MA operations in current LoRaWAN, this class of MA proposals additionally makes minor modifications to the ALOHA protocol. An example is RS-LoRa proposed in [14]. As depicted in Figure 2, RS-LoRa uses periodic beacon signals to coordinate the channel access behaviors of end devices. An end device firstly listens to the latest beacon signal and then determines the channel number, SF, and transmission power for its transmission. RS-LoRa particularly introduces a random time offset in addition to the standard ALOHA operations. The available time offset candidates are determined by subtracting the packet airtime from the period of beacon transmission.

Time-Domain Channel Segmentation

As the term suggests, this type of MA proposals allows end devices to share a wireless channel by introducing channel segmentation in the time domain as depicted in Figure 3. Each end device transmits only in its uniquely assigned time slot for interference avoidance. However, clock synchronization is a critical requirement. Typically, gateways need to act as centralized controllers for global synchronization. In addition, the design of time slot allocation algorithms and block acknowledgement techniques is needed.

- Network Synchronization and Scheduling Entity (NSSE) [15]: NSSE uses a single channel for clock synchronization and data collection. In the synchronization process, a reply from a gateway contains the current time slot index, time offset in the current time slot, and assigned time slot indexes for an end device to transmit. Slot allocation is performed in a first-come-first-serve manner. A guard time interval is included at the end of each time slot. This renders NSSE able to tolerate small slot desynchronization caused by the clock drift among end devices and the signal propagation delay between end devices and gateways.
- TS-LoRa [16]: Instead of directly informing end devices of assigned slot indexes via gateways, TS-LoRa distributes the slot mapping tasks to end devices. This is achieved by having each end device use a hash function to convert its network address into a slot index. Each network address is generated by a network server and guaranteed to yield a unique slot index. For clock synchronization of the current transmission round, TS-LoRa employs a bitmap-based acknowledgement message regarding the previous transmission round. Particularly, each time slot in TS-LoRa contains two guard time intervals at its beginning and end.

Machine Learning

Leveraging machine learning algorithms at end devices for distributed channel access have emerged recently. A pioneering proposal is DeepSense presented in [17]. Specifically, DeepSense is a wireless signal classifier mainly for carrier sensing regarding various LPWAN technologies (*e.g.,* LoRaWAN, Sigfox, and IEEE 802.11ah). It resorts to two deep learning architectures: spectrogram+convolutional neural network

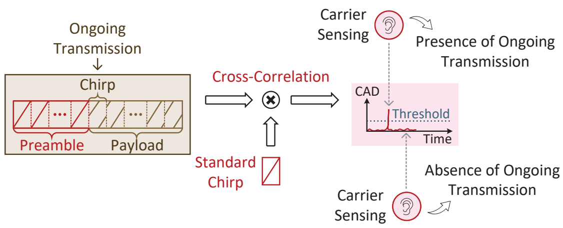

Figure 4. The use of CAD for MA support.

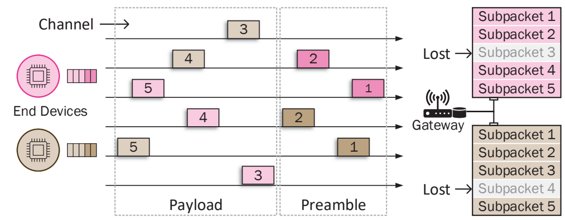

Figure 5. TS-enabled channel access in LoRaWAN.

(CNN) and dilated CNN+recurrent neural network (RNN). The former one transforms signal samples within a fixed carrier-sense window into a spectrogram. A pre-trained CNN is then applied with a certain signal class as the output. To further achieve the use of variable carrier-sense window size, the latter approach chooses a dilated CNN to automatically compute a compressed representation of the signals. An RNN is utilized thereafter to increase the confidence of the output signal class by adaptively selecting carrier-sense window size for different LPWAN protocols.

Channel Activity Detection (CAD)

As a recently introduced carrier-sensing function in LoRaWAN, CAD renders it possible to detect LoRaWAN signals even traversing below the noise floor. Typically, given a target channel and SF, CAD detects a signal preamble via the cross-correlation between received signal samples and a pre-generated standard CSS chirp as illustrated in Figure 4. A strong correlation result indicates that a signal with the same SF adopted is occupying the target channel.

- p-CARMA [18]: Based on multiple results of CAD, p-CARMA has an end device firstly compute a probability value p on its own and then perform p adaptation with additional information from gateways. If a channel is occupied by other end devices, it waits for a random duration and then conducts CAD again. The p value determines the transmission probability when it observes a clear channel thereafter. This design stems from the fact that CAD can only detect LoRaWAN signal preambles and may lead to false negatives regarding LoRaWAN signal payload transmissions.
- LMAC [19]: In addition to the signal preamble, LMAC shows that CAD can also achieve LoRaWAN signal payload detection. Based on the results of a fixed number of CAD performed in a customized interval, the transmission behaviors of end devices are defined with three versions. In LMAC-1, an end device transmits immediately when CAD yields the result of "channel clear". LMAC-2 additionally introduces a distributed channel switching operation at end devices when the current channel is deemed busy. To further help end devices select better channels, LMAC-3 has gateways send channel status-related messages to provide a global view of the channels.

Deterministic and Synchronous Multichannel Extension (DSME)

Presented in [20], DSME-LoRa implements the existing DSME protocol of the IEEE 802.15.4e standard in LoRaWAN. DSME-LoRa inherits all the basic operations in the conventional DSME protocol. Specifically, DSME-LoRa aims at coordinated transmissions from synchronized LoRaWAN end devices. This is achieved with the use of multiple superframes. Specifically, each superframe consists of a beacon slot, contention access period (CAP), and contention free period (CFP). End devices are synchronized in the beacon slot by receiving a beacon signal from LoRaWAN gateways. In CAP, end devices perform carrier-sensing based on the preamble-based CAD and transmit when a target channel is deemed clear. Each end device choosing to transmit in CFP is allocated with a unique time slot for guaranteed transmission.

Telegram Splitting (TS)

TS is the core MA technique of MIOTY, a production-level LPWAN communication solution for Industry 4.0 applications [21]. TS splits a LPWAN packet into multiple subpackets and transmits them at different times and channels as depicted in Figure 5. Because of the reduced on-air time of each subpacket, the chance of collisions with other packets is low. It is worth noting that while TS uses multiple channels to distribute the subpacket transmissions, adopting TS with a single channel can also withstand heavy co-channel interference and hence provides better MA

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Table 1. Comparison of the representative MA proposals for LoRaWAN. SDR: Software-defined radio.

MA Proposal	Type	Computational Cost		Evaluation Approach	Network Energy Consumption	PRR	Goodput
		Gateway	End Device				
RS-LoRa [14]	Enhanced ALOHA	Medium	Medium	Simulation based on ns-3	N/A	Low	Low
NSSE [15]	Channel Segmentation	High	Low	Simulation based on ns-3	Low	High	Medium
TS-LoRa [16]	Channel Segmentation	High	Low	Experiment with LoRa chips	Low	High	Medium
DeepSense [17]	Machine Learning	Low	High	Experiment with LoRa chips and SDR	N/A	N/A	N/A
p-CARMA [18]	CAD	Low	High	Simulation based on ns-3	High	Medium	Medium
LMAC [19]	CAD	Low	High	Experiment with LoRa chips	High	High	High
DSME-LoRa [20]	DSME	Medium	Medium	Experiment with LoRa chips	N/A	Medium	N/A
TS [21]	TS	Medium	Medium	In-situ tests for target applications	N/A	N/A	N/A

performances than ALOHA. Moreover, even when several subpackets are corrupted, the others can also be successfully received and only the lost ones need to be retransmitted if necessary.

Comparison of MA Solutions

Regarding the MA solutions for LoRaWAN above, we provide a comparison as shown in Table 1. For the computational cost, the comparison is performed for both gateways and end devices according to the involved computations in the MA solutions. For the comparison in terms of network energy consumption, packet reception ratio (PRR), and goodput, we observe the corresponding performance evaluation results presented in these studies and estimate the performances under the same network settings.

Computational Cost: In comparison with the other types of MA techniques, the channel segmentation-based solutions (*i.e.,* NSSE and TS-LoRa) incur higher computational cost at the gateway side mainly due to the procedures of clock synchronization and time slot allocation. At the end device side, however, they are relatively simple and lightweight since end devices only need to wake up and transmit at their assigned time slots. This is different from the carrier sensing-based solutions (*i.e.,* DeepSense, p-CARMA, and LMAC) where gateways are hardly involved in the MA process, whereas end devices need to check the channel status before transmissions.

Network Energy Consumption: While NSSE and TS-LoRa need clock synchronization among gateways and end devices, end devices only need to wake up at their own time slots and can sleep for the rest of the time. However, p-CARMA, and LMAC entail continuous channel listening at end devices, which leads to higher network energy consumption.

PRR: Since RS-LoRa still operates in the conventional ALOHA fashion, their achievable PRR is in a low level in comparison with the other types of solutions. In NSSE and TS-LoRa, the transmission of each end device is mapped to a unique time slot, thereby eliminating signal interference and incurring tremendous PRR increment. Regarding the carrier sensing-based solutions, LMAC achieves higher PRR than p-CARMA. This is because the CAD used in LMAC can detect both signal preamble and payload. This is also why LMAC is better than DSME-LoRa which leverages preamble-based CAD in CAP.

Goodput: RS-LoRa features the lowest goodput among our considered types of MA proposals. Due to the need of control message exchange for clock synchronization before end device transmissions, the channel segmentation-based solutions achieve lower goodput than the carrier sensing-based ones.

Future Perspectives for LoRaWAN MA

By considering the limitations of the MA solutions above, we present several research insights worthy of investigation in the future.

Low-cost CAD Design

As described in Table 1, LMAC [19] shows the best MA performance in terms of PRR and goodput. Unfortunately, the included CAD operation resorts to continuous cross-correlation computation, which renders the computational overhead and energy consumption in an extremely high level at end devices. One plausible solution is to have end devices switch into sleep mode for energy saving after observing a busy channel via CAD. According to the different performance requirements of target applications, one can simply configure the sleep duration randomly or adjust the sleep duration adaptively based on the estimation of ongoing packet length. In the latter case, end devices can further add several CAD time slots before sleep to determine whether the current CAD is applied to the signal preamble or the payload of an ongoing packet. This is based on the observation that the consecutive cross-correlation peaks have a similar height when CAD is applied to a preamble and become different in the case of packet payload [19]. As a result, it is possible to estimate the rest length of an ongoing transmission based on the used SF and the maximum payload size allowed in the target applications.

MA Support for Heterogeneous End Devices

All the existing LoRaWAN MA proposals consider homogeneous LoRaWAN end devices that operate under the same rules (*e.g.,* duty cycle and data generation interval) and have the same priority for uplink transmissions. This network model, however, does not accommodate the requirements of many real-time IoT applications (*e.g.,* vehicular networks and industrial IoT). In these applications, delays and deadline guarantee on packet delivery are more important than the long-term PRR and throughput targeted in the homogeneous case. One possible approach to provide such guarantees is to have such an end device switch into transmission-only mode and send a deadline-constrained packet multiple times in the same channel within a certain time duration less than its required deadline. This design is based on the assumption that the corresponding LoRaWAN server can successfully receive the contained information at least in one of the transmitted packets. Evidently, this approach can aggravate network congestion and hence affects the reception performance of regular packets. Under these circumstances, it is crucial to develop further algorithms to adjust the number of transmitted packets within a certain duration, distribute such packet transmissions over multiple available channels, and so forth.

In-situ Tests of MA Proposals

The performance test of most LoRaWAN MA proposals is limited to customized simulators or small-scale networks with simplified network functions. In practice, however, full-fledged LoRaWAN systems operate in a much more complicated way. For example, practical end devices transmit in a broadcast manner rather than solely sending to a specific gateway. Moreover, various ADR algorithms are implemented to adjust SF based on wireless link budget. Thus, the real-world performance of the existing approaches will disaccord with that provided in the literature. Accordingly, it is of paramount importance to apply newly designed MA proposals to large-scale LoRaWAN systems for in-situ tests and then confirm their merits in real-world environments. To this end, we have built an SDR-based testbed that is available for external users after prior contact [22]. It can be used to evaluate LoRaWAN MA solutions under controllable and repeatable scenarios to benchmark different approaches. Furthermore, its architecture allows coexistence testing between commercial solutions and existing SDR implementations while also enabling the creation and release of reference data sets for further use.

Conclusion

This article explores the MA issues behind the fact that current LoRaWAN is not yet a mature technology for large-scale IoT networking. We start with providing several use cases of large-scale LoRaWAN. We then deeply analyze the reasons that LoRaWAN cannot withstand massive interfering links. By categorizing and comparing the existing MA proposals, we provide a detailed overview of the state of the art for better MA support in LoRaWAN. Finally, we provide several research insights regarding LoRaWAN MA.

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