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A Novel Network Architecture and MAC Protocol for Confirmed Traffic in LoRaWAN

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ABSTRACT This paper presents a novel network architecture called edge acknowledging and a MAC protocol to enhance the reliability of LoRaWAN confirmed messaging. The edge acknowledging exploits the great capability of the gateway and high reliability of the cable-based connection between the gateway and net server to reduce the vulnerable period of the confirmed messaging. The new MAC protocol is time-slotted and constrains the end nodes from the contention for the channel to reduce the energy consumption. The performance of the combination of edge acknowledging and the new MAC protocol is evaluated in simulations and analysis using the metrics of packet reception ratio, end-to-end delivery probability, energy consumption per packet, and delay. The results show that our edge acknowledging architecture and the cooperating new MAC protocol obtain 4 to 10 times packet reception ratio, 2.5 times end-to-end delivery probability, and 97% lower energy consumption of the combination of the conventional LoRaWAN architecture and CSMA-like protocols for confirmed messaging. While the delay of our new solution for a successfully confirmed transmission increases by a factor of 20 to 30 in the large-scale network consisting of 500 nodes.

INDEX TERMS LoRaWAN, architecture, MAC, low power, packet reception ratio, end-to-end reliability, delay, confirmed messaging.

I. INTRODUCTION

Low power wide area networks (LPWANs) accelerate the growth of the Internet of Things (IoT) market. Until 2021, over 680 million LPWAN connections are expected [1]. The market is mainly shared among the four technologies and LoRa constantly gained the leading position since 2017. It operates in the unlicensed sub-GHz spectrum for most areas in the world, enables low data-rate communications over long distances, and targets the Internet of Things (IoT) and machine-to-machine (M2M) applications [2]. The accompanying MAC protocol named LoRaWAN [3] was proposed by the LoRaWAN alliance to set up wide area networks (WANs). Each node in a LoRaWAN network operates in one of three classes: Class A, Class B, and Class C. To attain the highest energy efficiency, Class A nodes spend most of their time in sleep mode and wake up only when it is necessary to upload data. Subsequently, two receive windows are opened at specific times for downlink transmissions. In contrast, several receive windows are scheduled to each node for downlink

messages using synchronized beacons in the Class B mode. Downlink messages can reach the end node more promptly in Class B mode than in Class A, but the energy consumption of the Class B mode is higher as the end nodes open receive windows periodically. Class C nodes keep their receive window constantly open and as a result, feature the highest energy consumption of all classes. In most applications, Class A mode is used because the devices are usually battery powered and the network needs to scale, for example, in smart city applications, several hundred or even thousand nodes have to be supported by a single gateway. LoRaWAN MAC adopts the ALOHA protocol where nodes start to transmit a packet without any perception of the channel status once data transmission is requested by the application layer.

While LoRaWAN networks are increasingly deployed worldwide, there are still many issues that need to be addressed. First, ALOHA and its variants suffer from low throughput and low packet reception ratio (PRR) [4]. For example, smart gas and water meters are supposed to upload daily data in today's smart city applications using confirmed messaging. If there are thousands of devices deployed in an area with several super high-rise residential buildings, which

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is a common scenario, especially in Asian countries, tens of thousands of transmissions, including retransmissions, may occur in one community every day [5], [6]. Although ALOHA is simple to implement on a resource-constrained embedded end node, it is inadequate for such massive machine-type communication because its throughput and PRR are usually very low because of the many collisions if numerous nodes start to transmit simultaneously. Furthermore, end nodes require energy for each transmission; thus, frequent retransmissions, which is a necessity for confirmed messaging, shortens the lifetime of the nodes. In [7], the authors simulated the performance of the LoRaWAN ALOHA protocol. Packets with uniformly distributed payload lengths between one and 51 bytes are assumed to arrive at each node according to a Poisson process. They obtained a channel capacity of 18% usage with an offered load of 0.48, which is similar to the pure ALOHA throughput. The work presented in [8] shows that the maximum throughput achievable for ALOHA is 8% at the offered load of 0.25 when all uplink packets need to be confirmed. In addition to the complete confirmed traffic, the scenarios in which both confirmed and unconfirmed traffic is used are investigated as well. The authors of [9] build a MATLAB-based simulator to study how confirmed traffic negatively impacts the network performance and they found that the throughput for both unconfirmed and confirmed traffic reduces when the ratio between these types of traffic increases. Another MATLAB simulation work present in [10] investigates the cases that 100%, 33%, and 25% of end nodes request an acknowledgment and their results show that the packet error rate (PER) per node increases drastically with the percentage of nodes requesting ACK and the scale of the network. Moreover, the currently proposed solutions to address the low performance of confirmed traffic breaches the security mechanism of LoRaWAN [11], [12]. The authors of [13] proposed an acknowledgment aggregation scheme in which several devices and received packets are acknowledged by ACKs incorporated into an “AggACK”. The problem with this approach is that LoRaWAN requires a message integrity code (MIC) attached to each packet to ensure data integrity and this MIC is specific for the end devices and even each packet [14]. Therefore, it is impossible to generate a common MIC for the “AggACK” packet which is valid for all destination nodes. A similar approach called group acknowledgment is employed in [15] which also aggregates acknowledgments of uplink transmissions received simultaneously from multiple end nodes. This scheme suffers from the same security issue as the previous one.

If one of the many protocols using carrier sense multiple access (CSMA) is used, the throughput and PRR performance improve; however, the power consumption is still an issue. The simulation work in [16] explored p-CSMA with various persistence values and node number settings. For the test cases with no hidden area, the highest PRR of 63% was achieved with a persistence value of 0.25 and a node number of 20, which is much better than that of slotted

ALOHA. However, this work does not investigate the energy consumption for transmission and carrier sensing, where one has to consider that carrier sensing consumes more power than ALOHA. In [17], the authors proposed a CSMA-based protocol called LMAC to improve the performance over ALOHA in terms of PRR, throughput, and energy consumption. More than 90% of transmissions succeed independent of the offered load, and the energy consumption per successful transmission is maintained at approximately 75 mJ which is 2.38 times lower than that consumed by ALOHA. LMAC achieves a high PRR and low power consumption because it uses 16 uplink channels to simultaneously collect packets from nodes in the unconfirmed mode. Therefore, the transmission collisions and carrier sense duration are significantly reduced. However, the LoRaWAN gateway can support only one downlink channel simultaneously, which implies that only one uplink transmission can be acknowledged for the confirmed messaging applications, even though 16 uplink packets are received by the gateway. Thus, the high throughput and PRR of LMAC are only achievable in unconfirmed transmission scenarios. In addition, LMAC adopts a continuous listening scheme such as the conventional CSMA protocol, thus the energy consumption is still very high. In particular, for confirmed transmissions, the limitation in the downlink leads to more uplink retransmissions and channel listening activities on each node.

A third issue is an evaluation of the packet delay. Up to date studies either investigated the delay performance of standard LoRaWAN Class A [18] using ALOHA or other classes [19]. The delay performance of the state-of-the-art protocols is usually ignored in many studies since LoRaWAN is regarded as a low data rate technique and for the lowest modulation scheme, the transmission duration of a packet with the maximal allowed size could be more than 2 s. Apart from the on-the-air duration, the CSMA-based MAC protocols impose more delay as an end device defers its transmission once it determines that another transmission is in progress. However, some applications, such as emergency applications [20], [21] and quick response of smart home control [22], require prompt messaging. Thus, we suggest that the packet delay performance of a novel protocol for LoRaWAN should be evaluated as well.

The contributions of this work are as follows.

- We analyzed the confirmed messaging under the conventional LoRaWAN architecture and MAC protocol, as well as its failure scenarios.
- We propose a novel network architecture, called edge acknowledging (EACK) and a contention-constrained p-persistent carrier sense multiple access (CCP) protocol to improve the reliability of confirmed messaging in LoRaWAN.
- We simulated and discussed the performance of the new architecture in combination with a novel MAC protocol using the metrics of PRR, end-to-end delivery probability, average energy consumption per packet, and delay.

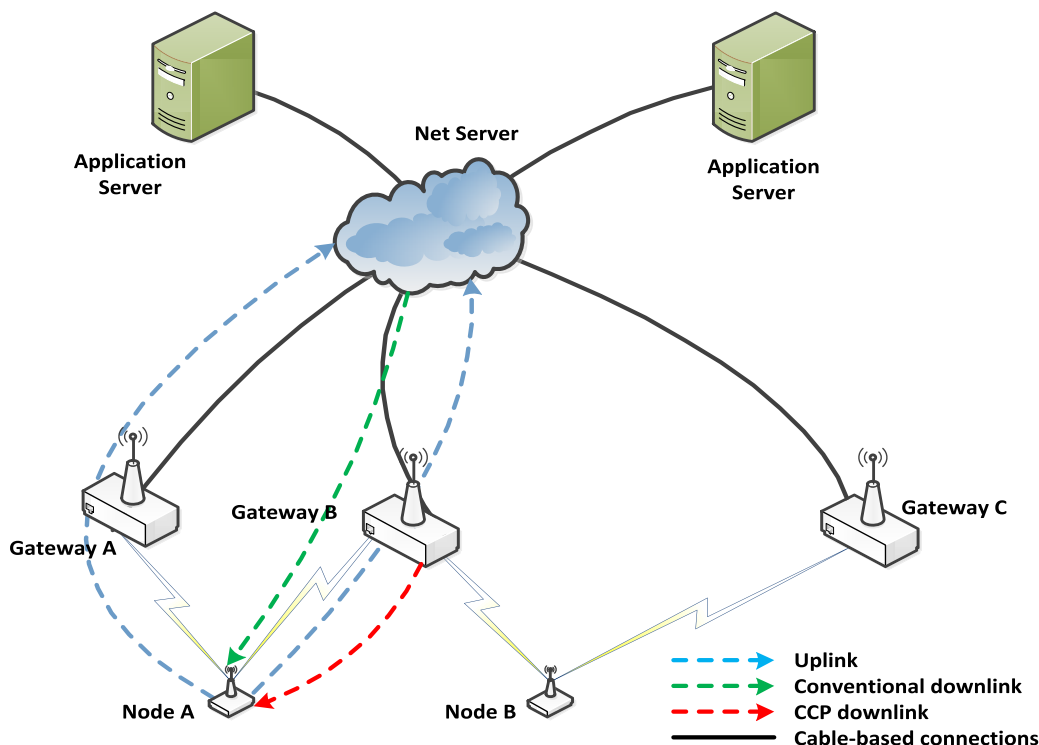


FIGURE 1. EACK and conventional LoRaWAN network architectures.

The remainder of this paper is organized as follows. Section II introduces the background knowledge of LoRaWAN and Class A mode. Section III presents the design of the proposed network architecture. Section IV describes the simulation settings, and the results are presented in Section V. Finally, Section VI concludes the paper.

II. LoRaWAN CLASS A PRIMER

Fig. 1 illustrates the LoRaWAN network architecture, where the end nodes scatter around gateways at a one-hop distance [23]. The blue dashed arrow denotes an example of uplink transmissions initiated by the end node A. Both gateways A and B receive the packet because node A transmits the packet in a broadcast manner. The packets are forwarded by both gateways simultaneously to a central net server, which forms multiple uplink forwarding. After the data has been collected on the net server, the application servers subscribe to it according to their needs. Conventionally, this uplink process is transparent for gateways, as they forward packets without any modifications. Packet security checks and parsing are carried out at the net server, where the subsequent acknowledgment is generated accordingly and sent to the gateway. There are two messaging types defined in LoRaWAN, which are confirmed and unconfirmed. For the former type, the net server generates an acknowledgment that is encapsulated into the header section of a LoRaWAN packet to confirm the uplink transmission whereas, for the latter, the net server will make no response. In addition to the acknowledgment

in the header, the net server may also encapsulate downlink data which is network control information or user data into the payload section of the packet. In comparison with the possible multiple uplink forwarding, downlink transmission to a specific end node is allowed by only one gateway at a time, which is selected by the net server on certain criteria, such as the signal-noise ratio (SNR) or the latency of a previous uplink transmission initiated by the same end node. This network architecture benefits the implementation and cost of the gateway but causes high latency for confirmed messaging as the acknowledgment is generated at the net server that is deployed in the cloud and connects to the gateways via a cable-based Internet connection. After receiving a packet from the net server, the selected gateway competes for channel access within two predefined time windows to transmit the downlink packet. Fig. 2 illustrates the timing of transmission (TX) and reception (RX), which are carried out on an end node. The receive windows $RX1$ and $RX2$ are opened $RX1_DELAY$ and $RX2_DELAY$ s after the end of the TX, respectively. $RX2$ is allocated in case $RX1$ is occupied by an earlier transmission, and it is discarded if a packet is received at $RX1$ by the end node. In the confirmed messaging mode, an end node may retransmit (ReTX) the same packet again at $ACK_TIMEOUT$ seconds after the start of $RX2$, as shown in Fig. 2, if it does not receive the acknowledgment in one of the two receive windows for the last uplink transmission. Fig. 3 shows two failure scenarios for confirmed messaging. In the first failure scenario, the uplink packet of Node A

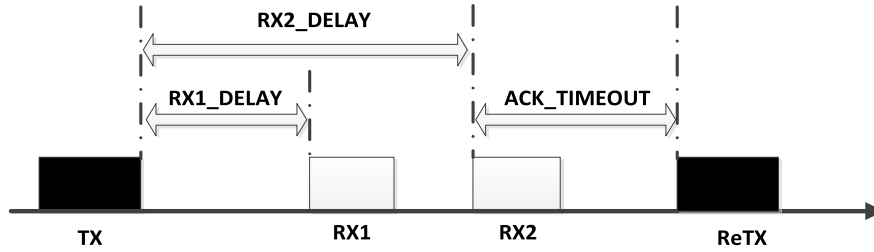


FIGURE 2. LoRaWAN Class A end node TX and RX timing for confirmed messaging.

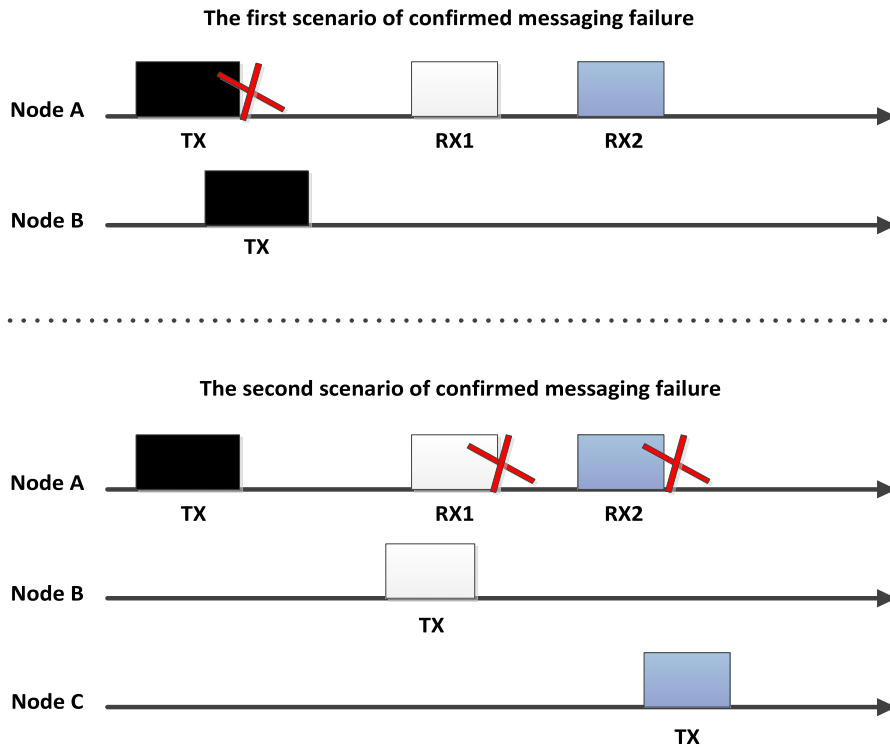


FIGURE 3. Collision circumstances for confirmed messaging. The collision might occur on different channels if multiple channels are allowed: the collision in the first scenario occurred on the “black” channel, and the RX1 and RX2 of Node A are impacted by the transmissions of Node B on the “gray” channel and Node C on “blue” channel, respectively.

collides with the uplink packet of *Node B* when the two packets are transmitted on the same channel. In the second scenario, the reception of the acknowledgment collides with an uplink packet of *Node B* during *RX1* and *Node C* during *RX2*. Note that the collisions occur on three different channels at most, which are illustrated in black, gray, and blue colors respectively. As a result, the probability of a collision for confirmed messaging is much higher than that for unconfirmed messaging, which merely requires the success of the uplink transmission.

III. DESIGN OF EACK ARCHITECTURE AND CCP

This section presents the design of the EACK architecture and the CCP MAC protocol to enhance the reliability, especially for confirmed messaging, compared to ALOHA and CSMA similar protocols.

A. EACK

The conventional LoRaWAN architecture is based on cloud network services in which the uplink packet is inspected and the corresponding acknowledgment is generated. As a result, an end node needs to wait up to one second, as specified by LoRaWAN [24], which includes the Internet round-trip time and the processing time on the net server. Thus, confirmed messaging is more vulnerable than unconfirmed messaging, as either an uplink or an acknowledgment packet collision leads to a transmission failure. To solve this issue, we propose a new EACK architecture called edge acknowledging (EACK), in which the uplink packets are acknowledged by a specific gateway deployed in the vicinity of the transmitting end node, rather than by the net server installed in the cloud. The red arrow in Fig. 1 illustrates the fast acknowledgment provided directly by gateway B. As a result, the

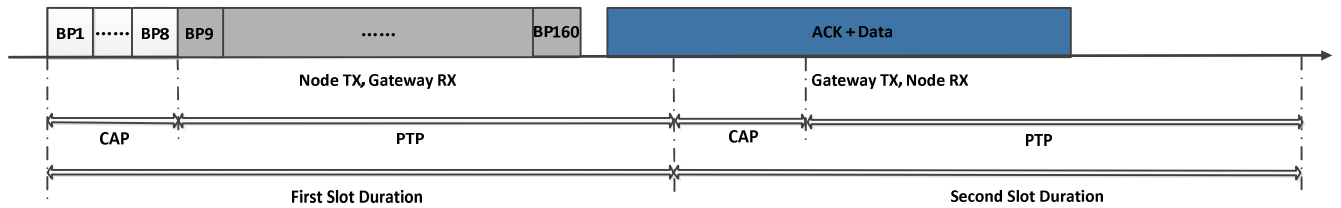


FIGURE 4. Two-way communication with ACK + data packet. The grey and blue shaded parts represent uplink and downlink transmissions, respectively.

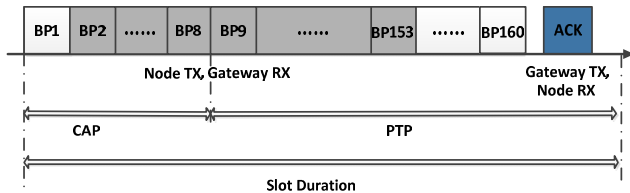


FIGURE 5. Two-way communication with ACK packet.

success ratio for confirmed messaging is roughly doubled for all time-slotted MAC protocols, such as slotted ALOHA or p-CSMA, because the transmission of the acknowledgment is ensured once the uplink packet transmission is successful. To make the EACK work, the net server needs to send a copy of the device addresses (devAddr) and network session key (NwksKey) [3] to gateway B either after node A has joined the network or after the first uplink transmission. The net server maintains these two pieces of information permanently and distributes or withdraws them on demand. For example, if the SNR of an uplink transmission from node A to gateway B is better than that to gateway A, then gateway B is selected to implement the fast ACK for the node A. If at a later point in time Node A travels to an area where gateway C is deployed, the devAddr and the NwksKey are removed from gateway B and sent to gateway C to continue the fast ACK services. After the uplink packet is successfully delivered to the gateway, it is forwarded to the net server via the TCP/IP protocol.

B. THE PROPOSED MAC PROTOCOL

Fig. 4 and 5 illustrate the design of our proposed MAC protocol which is called the contention-constrained p-CSMA (CCP). It is based on time slotting and consists of a contention access period (CAP) and a packet transmission period (PTP). The CAP is divided into eight backoff periods (BP), in which all end nodes start with a random backoff in the range from 0 to 7 BPs and then, access the channel according to the rule of the conventional p-CSMA protocol. As a result, after 0 BP backoff and carrier sensing in BP1, an end node might earliest start transmission in BP2 of CAP, which is illustrated in Fig. 5, while if the end node takes 7 BPs backoff and senses carrier in BP8 for idle, it might start transmission in BP9 of PTP at the latest, as illustrated in Fig. 4. All other nodes that sense the channel as busy enter sleep mode immediately to conserve energy and wake up again at the beginning of the next slot to resume the channel contention.



FIGURE 6. End-to-end link comprising a LoRa radio connection which is indicated as a dashed line and a cable-based connection which is indicated as a solid line. The notations EN, GW, and NS represent end node, gateway, and net server, respectively.

After receiving an uplink packet, the gateway transmits either an ACK packet, as illustrated in Fig. 5, or an ACK plus data packet, as illustrated in Fig. 4, if the net server has data to be sent to the node. For the former scenario, two-way communication is completed in one slot as the ACK packet duration is very short. In the latter scenario, the two-way communication spans over two consecutive slots because the length of the ACK + Data packet is too long to be accommodated in a single slot. Note that the transmission of ACK + Data is always immune from being collided by other transmissions because any node attempts to access the channel in the second slot will sense the channel for busy during the CAP of the second slot and that the gateway is allowed to transmit only one downlink packet to a specific node each time it receives an uplink packet.

C. ANALYSIS OF THE END-TO-END RELIABILITY

As shown in Fig. 6, the successful delivery of an uplink packet in both conventional and our solutions relies on the qualities of two links: the link between end node (EN) and gateway (GW), and the link between (GW) and net server (NS). The GW to NS link is usually cable-based which is highly reliable, and if some standard messaging protocol for the Internet of Things (IoT) is used, such as Message Queuing Telemetry Transport (MQTT) [25], the GW to NS link quality can even be more enhanced by choosing the quality of service (QoS) level 1 that guarantees a message is delivered at least one time from the GW to NS [26]. On the contrary, the link quality of EN to GW is much lower if numerous end nodes contend for the access of the media. LoRaWAN specification defined up to 8 times of retransmission if an end node fails to receive the acknowledgment from the net server for each of its confirmed uplink messages. However, the probability of confirmed packet loss is still very high even with these end-to-end retransmissions in the conventional LoRaWAN architecture and MAC protocol.

The end-to-end delivery probability is defined as the fraction of the number of successfully delivered packets over the

total number of uploaded. For conventional LoRaWAN with p-CSMA, this probability, p_C can be derived to be:

$$p_C = 1 - (1 - p_C^L p_C^C)^N \quad (1)$$

where p_C^L and p_C^C are defined as the fraction of successfully transmitted packets on the LoRa link (between an end node and a gateway under conventional architecture) and cable link (between the gateway and the net server) respectively. N denotes the maximum retransmission times initiated by the end node if it does not receive an acknowledgment from the net server. Note that we still account the packet loss probability between the gateway and net server into p_C^C if QoS level of MQTT protocol is set to 0. If the QoS of MQTT is set to 1, p_C^C is equal to 1. As a comparison, our EACK + CCP solution aims on improving the reliability of the end node to gateway link compared with the conventional LoRaWAN. The end-to-end delivery probability for our solution, p_E is given by:

$$p_E = [1 - (1 - p_E^L)^N] p^C \quad (2)$$

where p_E^L denotes the probability that an uploaded packet is successfully transmitted to and acknowledged by the gateway under EACK architecture. Note that the N times of retransmission is only applied to the end node to gateway link, and for the gateway to net server link, we adopt the MQTT delivery service only once without any further higher level retransmissions.

IV. SIMULATION SETTINGS

To assess the performance of our proposed EACK architecture and CCP protocol, we conducted simulations in MATLAB using the following settings.

- The number of end nodes was 500, and the simulation for each specific setting was conducted 10 times.
- The duration for each simulation iteration is set to 200 seconds.
- Poisson traffic with a rate parameter in the range of 1 to 24 with a step increment of 1 was used.
- The average time interval of packet arrival events is 0.2 seconds on average for each node.
- The uplink and downlink packet reception rates without collision were both set to 98%. This value is a statistic fraction drawn from an experiment where a transmitter continuously transmits 255-bytes packets to a receiver that is placed 9 m away from the transmitter [27].
- All uplink packets request an acknowledgment from the gateway, and the downlink packets have the same length as the uplink packets.
- The LoRa chip operates with a supply voltage of 3.3 V, and the supply current in the transmit and receive modes are 20 mA and 5 mA, respectively [28].
- All devices are stationary and located in a collision domain, that is, all devices mutually interfere with each other.
- The network offered load is defined as the ratio of the total number of packets offered to the network to its

capacity. An offered load of 1 equates to the situation where the end nodes on the network provide sufficient traffic to completely fill the channel without any time gap.

- The persistence parameter p is set to 0.1 for both p-CSMA with LoRaWAN and CCP with EACK.

The metrics that we used to evaluate the performance are PRR, end-to-end delivery probability, energy consumption per successfully acknowledged packet, and delay. Only when a packet is acknowledged by the gateway is considered a successful delivery. An uplink transmission without an acknowledgment is regarded as a failed transmission. The delay is measured from the storage of the uplink packet in the buffer of a node to the reception of the corresponding acknowledgment sent from the gateway.

V. RESULTS

The performance of p-CSMA with the conventional LoRaWAN architecture and CCP with EACK architecture were evaluated through simulations performed with the settings described in Section IV.

A. PRR PERFORMANCE

The reliability is evaluated in two levels: PRR between end nodes and gateway, and end-to-end delivery probability. Fig. 7 shows the mean PRR performance of p-CSMA with LoRaWAN architecture and CCP with EACK architecture. The PRR of p-CSMA with LoRaWAN starts at a level of 5.6% which is extremely low. We initially loaded a packet into each end node and as a result, the network reached a traffic saturation at the begging of the simulation as 500 nodes attempt to grab the same channel simultaneously. After the begging, PRR declines slowly from 3.6% as the number of successfully delivered packets is almost constant but the total number of the loaded packets is increasing. Note that we assumed the transmission of downlink acknowledgment from the net server to the gateway via a cable-based connection is always succeeded, which is reasonable as the packet loss on this link is very low compared with the LoRa link or even never occurs if the high quality service of MQTT is used. In comparison, the performance of CCP achieves nearly 58% PRR at the lowest offered load. It degrades gradually to approximately 12% at the offered load of 4.2, which is still approximately 10% higher compared with p-CSMA.

We also investigated the performance variation among the end nodes using the coefficient of variation (CV) [29], which is defined as follows:

$$CV = \frac{std(PRR)}{mean(PRR)} \quad (3)$$

where $std()$ and $mean()$ are functions to compute the standard deviation and mean of the PRR vector respectively. In Fig. 7, we have plotted the metric CV as a function of the offered load. Generally, the CV of CCP is much lower than p-CSMA which shows that the PRR performance fairness under CCP is better than p-CSMA. The CV of CCP remains

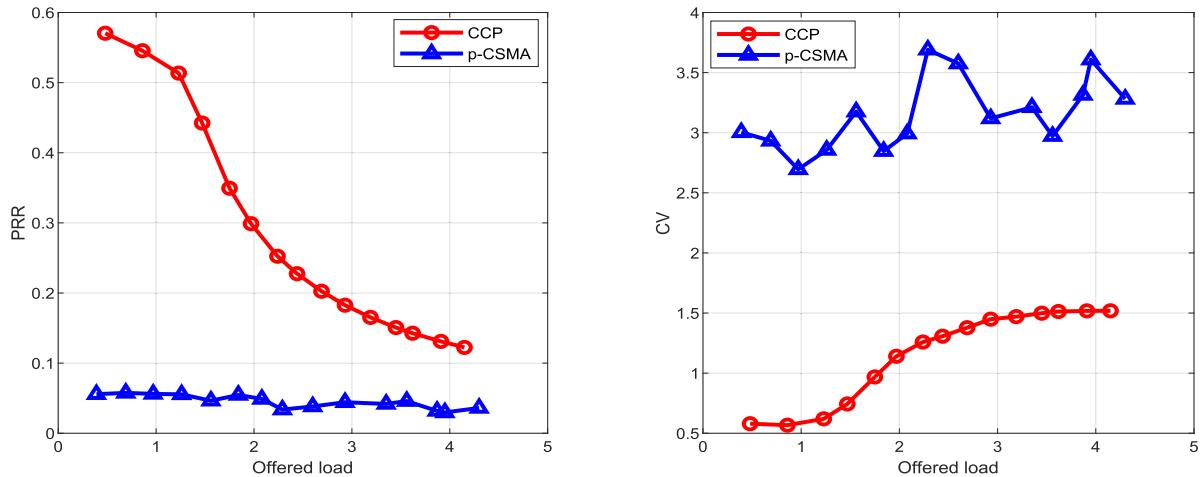


FIGURE 7. PRR and its coefficient of variation for classic p-CSMA + LoRaWAN and CCP + EACK. The node number is 500 and all nodes are provided with at least one packet.

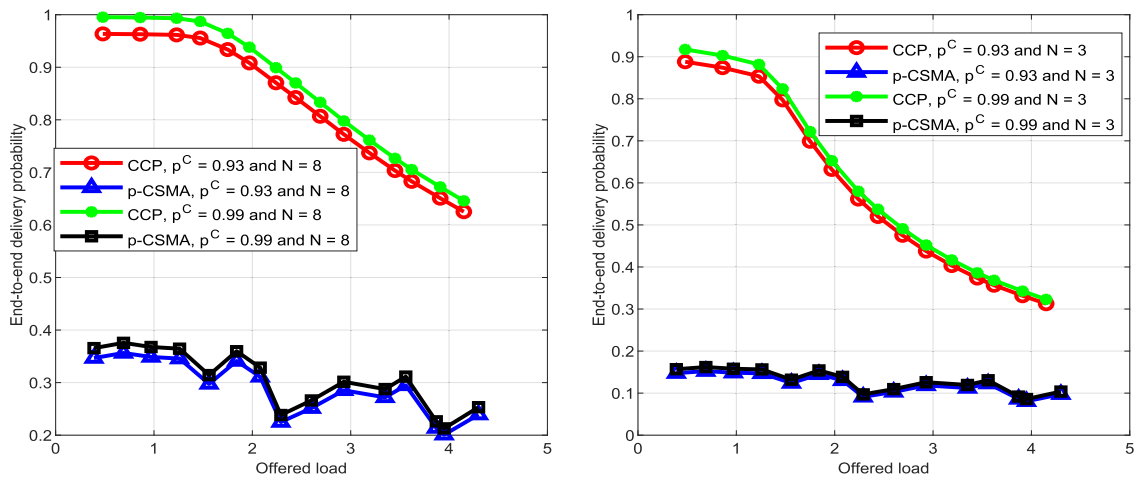


FIGURE 8. End-to-end delivery probability for conventional LoRaWAN + p-CSMA and EACK + CCP. The maximum retransmission times, N denotes the maximum retransmission times and is set to 8 and 3 respectively, and p^C denotes the probability that the gateway successfully forwards an upload packet to the net server.

constant at 0.6 until the offered load reaches 1.3, and after that, it increases gradually to 1.5 when a higher offered load is applied. The p-CSMA suffers from more than 2 times higher CV continuously, which fluctuates wildly in a range of 2.5 to 4.

B. END-TO-END DELIVERY PROBABILITY PERFORMANCE

The end-to-end delivery probability can be increased by using a retransmission mechanism. LoRaWAN standard defined that a confirmed upload packet can be retransmitted by up to 8 times from the end node to the net server. The end-to-end probability for conventional LoRaWAN with p-CSMA and our solution can be derived from (1) and (2) respectively and plotted in Fig. 8. The delivery probability of gateway to net server, p^C is set to 0.93 and 0.99 respectively [30]. It is notable that the end-to-end delivery probability significantly increases to 20% to 38% for the conventional LoRaWAN with

p-CSMA and 60% to 95% for EACK with CCP in the case of N is set to 8. When the packet loss on the cable-based connection is taken into account (reduces p^C from 0.99 to 0.93), the delivery probability for both conventional LoRaWAN and our solution is reduced by 3%. If the number of maximum allowed retransmission times is set to 3, the delivery probability of the conventional LoRaWAN with p-CSMA is reduced by half (approximately 10% to 15% as shown on the right side of the figure). On the contrary, the impact of fewer retransmission times on the delivery probability of EACK with CCP is substantially mitigated. Our solution attains a delivery probability that is continuously higher than 60% until the offered load of 2, and after that, it gradually declines to 30%. Moreover, the quality of cable-based connection between the gateway and net server influence the delivery probability in the same manner with the setting of N = 8, but slightly less.

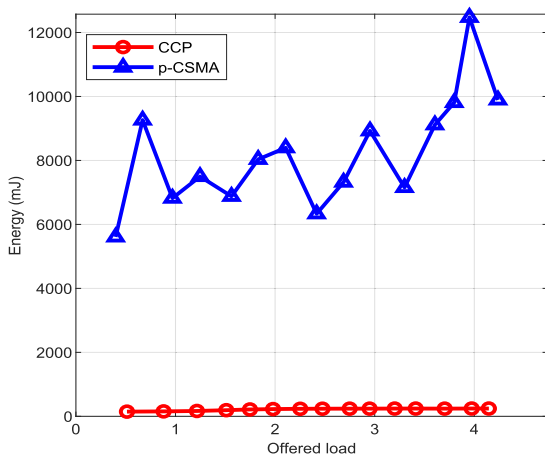


FIGURE 9. Energy performance of classic p-CSMA + LoRaWAN and CCP + EACK. It is defined as the fraction of acknowledged uplink packets assuming that the message delivery between the net server and the gateway is always ensured by the use of MQTT QoS 1 setting.

C. ENERGY PERFORMANCE

The simulation results for the evaluation of energy consumption are shown in Fig. 9. The energy consumption of p-CSMA with LoRaWAN starts at a very high level as numerous end nodes attempted to transmit at the begging of the simulation. When the offered load is below 3, the average energy consumption fluctuates in the range of 6000 mJ and 8000 mJ, and it increases gradually to the level of 10000 mJ after that offered load. This is due to the increasing carrier sense activities when more and more traffic is loaded to the end nodes. On the contrary, CCP performs much lower energy consumption overall offered loads. It increases slowly from 143 mJ at the offered load of 0.38 to 235 mJ at the offered load of 2.3. The energy consumption of CCP with EACK remains at that level as the total number of transmissions and carrier sense becomes constant when the offered load is very high.

D. DELAY PERFORMANCE

The last evaluation metric used to measure the performance of the CCP with EACK is the packet delay which is defined as the time interval between a packet being passed to the MAC layer and the packet arrives the gateway. Transmission delay of acknowledgment is not counted. Fig. 10 illustrates the mean delay of the packets that are acknowledged by the gateway in EACK architecture and by the net server in conventional LoRaWAN respectively. As all end node is loaded with a packet initially, the delay of CCP starts at a high delay of approximately 351 s, and it increases drastically to approximately 990 s at the offered load of 1.7. After that, the delay of CCP remains steady. In contrast, the p-CSMA achieves a much lower and stable delay performance. Its initial delay is approximately 10 s and rises slowly to only 52 s at the offered load 3.2. Similar to CCP, the delay of p-CSMA also reaches a steady value since the offered load of 3.2. The explanation for the steady delay for both protocols after

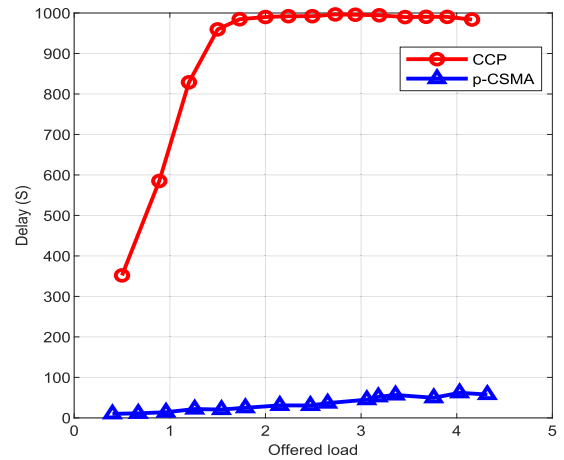


FIGURE 10. Delay comparison of p-CSMA + LoRaWAN and CCP + EACK. The delay is defined as the time interval between the instants when a packet is buffered and received by the gateway. The packets that are buffered but never transmitted or lost during the collisions need not be accounted for.

certain offered load is that: when the offered load is very high, the buffers in the nodes become quickly full, and in a first-in-first-out (FIFO) buffer, obsolete packets are discarded to retrieve the buffering space for the newly generated packets. Therefore, the packets are refreshed constantly in a saturated buffer, and the average age of the packets becomes stable.

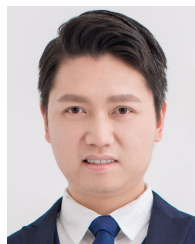
It should be noted that p-CSMA achieves low delay with significant sacrifices: a great number of packets is lost due to collisions and extremely high power consumption due to collisions and frequent carrier sense activities. Furthermore, it can be seen from the CCP plot that the delay decreases dramatically when the offered load becomes lower. We expect that our CCP protocol with EACK would achieve much lower packet delay in a network consisting of fewer end nodes (maybe the number of nodes is in the range of 10 to 50), which is another emerging application paradigm [31], [32] compared with the traditional large-scale applications.

VI. CONCLUSION

This study investigated the performance of a novel network architecture called EACK and a MAC protocol called CCP, which is specially designed to work with LoRa modulation. The evaluation metrics comprised the packet reception ratio, end-to-end delivery probability, energy consumption per packet, and packet delay. The classic p-CSMA, with a persistence value of 0.1 and the conventional LoRaWAN architecture was used as a benchmark to evaluate the performance of the CCP with EACK. Simulation results showed that, compared with p-CSMA with conventional LoRaWAN, CCP with EACK consumes approximately 97% less energy, attains 4 to 10 times of PRR, and 2.5 times of end-to-end delivery probability. The packet delay of the CCP with EACK is 20 to 30 times of p-CSMA with LoRaWAN. The results show that our proposed MAC protocol CCP and network architecture EACK are better able to fulfill high reliability and low power requirements and delay-tolerant LoRaWAN applications.

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