Improving Channel Utilization of LoRaWAN by using Novel Channel Access Mechanism

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***Abstract*—Low power wide area network (LPWAN) technology has been widely adopted in different Internet-of-things (IoT) services. Long range wide area network (LoRaWAN) is an evolution of wireless sensor network (WSN) directed to IoT concept, mostly used in private outdoor applications. The existing LoRaWAN operates following the simple ALOHA standards. Therefore, it suffers from high packet loss and supports a very limited number of nodes. For the application of LoRaWAN in dense networks, an efficient channel access mechanism is required in order to improve the efficiency and robustness. In this paper, we investigate a modified listen-before-talk (LBT) mechanism. Specifically, we propose LoRa-BED, LoRa-BEB and LoRa-BEH, channel access protocols to reduce collisions in high density environment. Our results demonstrate that the proposed protocols significantly improve the channel utilization and efficiency with a slight increase in energy per device while sensing the channel.**

***Index Terms*—LoRaWAN, carrier sense multiple access, distributed coordination function, medium access control.**

I. INTRODUCTION

Internet-of-things (IoT) devices are growing considerably and expected to reach 31 billion by 2020 [1]. A big chunk of these IoT devices constitute the low power wide area network (LPWAN). Specifically, the technologies such as LoRa [2], weightless [3], and Sigfox [4] are efficient in low power and long distance communication. Long range wide area network (LoRaWAN), network protocol of LoRa has been widely used in private outdoor applications such as smart cities, industrial, health care, agriculture. LPWAN operates in a star topology which is easy to manage, whereas the multi-hop network is relatively complex. In LPWAN, numerous devices are connected to a very few sink (gateway) devices. It is required to connect the maximum number of end nodes to a sink node, therefore, exposing to the risk of a large number of devices and their consequent output sharing the same medium.

Considering LoRaWAN in dense networks, the sink and the end nodes are using combinations of different parameters such as transmission frequency, transmission power, spreading factor and coding schemes to gain maximum diversity. These parameters are selected randomly depending upon few circumstances (e.g., path loss), to avoid collisions and to perform more robust communication. Given that the conventional LoRaWAN operates on a simple ALOHA protocol, the performance of this protocol dramatically declines, as the number of nodes approaches a few thousands. Therefore, it is recommended to substitute the conventional ALOHA protocol with an efficient channel access mechanism that increases efficiency and adds robustness while mitigating the risks the system was previously exposed to.

Scalability and capacity of LoRa has been a topic of keen interest in the field. Augustin *et al*. [5] simulated LoRa regarding its channel capacity and collision ratio for large number of devices by increasing the channel capacity. They elaborated that LoRa channel capacity usage is similar to Pure-ALOHA (P-ALOHA) having a maximum throughput of 18%. Different works e.g. [6], [7], [8], address large scale networks and provide answers to questions such as the number of maximum devices a gateway can support without deteriorating the performance significantly; and how the throughput and collisions of nodes varies as the network size increases, respecting the duty cycle limitations. Mahmood *et al*. [9] illustrated the degradation in coverage probability, because of co and inter-SF interference as devices increase in a single cell large scale network.

Duda *et al*. in [10] proposed carrier sense multiple access $CSMA-x$ protocol with LoRaWAN and simulated on NS-3 where they sense channel 10 ms before sending every packet. Using this approach, they improved the collision ratio whereby utilising a sample of large number of devices. Their protocol also consumes less energy as compared to LoRaWAN, while using more than 5000 devices in a network. Kouvelas *et al*. [11] developed p-CSMA protocol on NS-3 where they sense channel and send packets using different persistence values. They have also taken hidden devices into account for showing the results on a small scale LoRaWAN network. C. Pham [12] introduced listen-before-talk (LBT) mechanism on hardware and proposed $CSMA_{new}^{LoRa}$ protocol by using channel activity detection (*CAD*). He explained CAD reliability issues and how it can be adopted to LoRaWAN. He used two devices to show the performance of $CSMA_{new}^{LoRa}$ and discussed the increase in energy consumption with respect to *CAD* while using LBT mechanism.

In this paper, we discuss the LBT channel sense mechanism that a LoRaWAN could use to sense whether the channel is 'idle' or 'busy'. We also propose channel access mechanisms using the aforementioned sensing technique that help reducing the large number of collisions and optimising the channel utilization, such that maximum number of nodes can be connected to the gateway. We apply our protocols on large scale LoRaWAN network to study scalability of the proposed approach.

The rest of the paper is organized as follows:. Section II explains LoRa, the existing ALOHA protocol and channel sensing mechanism. Section III elaborates and discusses the three different protocols. Section IV explains the simulation results that validate the proposed protocols. Section V concludes this paper.

II. LoRa PHY and MAC

The LoRa technology generally follows IEEE-802.15.4 standard, which is used for low rate wireless personal area networks. It operates in the license free ISM bands of 433, 868, 915 MHz with duty cycle regulation of 0.1% to 1% for different regions. The LoRa consists three different bandwidths (BW) of 125 KHz, 250 KHz and 500 KHz, with the modulation scheme based on chirp spread spectrum (*CSS*). The transmission power (TP) can be adjusted from -4 dBm to 20 dBm and spreading factor (SF) can be varied in the range of 7 to 12. It also uses different code rate (CR) which is based on Hamming 4/5 to 4/8, to increase the robustness.

The time-on-air (ToA) is the time needed for a LoRa packet to transmit, and is given as [13],

$$ToA = T_{\text{pr}} + T_{\text{pl}}, \tag{1}$$

where preamble time, T_{pr}, and payload time, T_{pl}, can be calculated as follows

$$T_{\text{pr}} = (n_{\text{p}} + 4.25)T_s \tag{2}$$

$$T_{\text{pl}} = \left(8 + max\left\lceil \delta(CR+4), 0\right\rceil\right)T_s \tag{3}$$

$$\delta = \left(\frac{8PL - 4SF + 16CRC - 20H + 28}{4(SF - 2DE)}\right), \tag{4}$$

where T_s is symbol time which is equal to $2^{SF}/BW$. Table I is constructed using above equations by using different combination of SF and BW. Other parameter in above equations are, the number of included preambles, n_{p}, payload, PL, cyclic redundancy check, CRC, implicit header mode, H and low data-rate optimization, DE.

LoRaWAN is divided in to three classes: A, B and C, depending upon the application. Difference in these classes is because of their receiving windows. Class A opens two receiving windows at specific time after sending up-link data to the gateway. Therefore, this class consumes minimum energy and must be implemented in all the nodes. Class B is used for more down-links, hence it opens more receiving windows which are scheduled periodically by the network. Whereas, class C nodes have their receiving windows always open only except while transmitting, therefore, their energy consumption is highest among all three. In this paper we are considering class A type of LoRaWAN devices.

TABLE I: ToA_{max} using different settings of SF and BW

$Mode$	SF	BW (kHz)	ToA_{max} (ms)
1	12	125	9019.39
2	11	125	5001.22
3	10	125	2295.81
4	9	125	1250.30
5	8	250	353.54
6	7	250	199.81

TABLE II: *CAD* information [14]

SF	No. of symbols	*CAD* time (ms)	False detection %	*CAD* consumption (nAh)
7	2	2.67	0.17	2.84
8	2	5.39	1.27	5.75
9	4	19.15	1.90	20.44
10	4	38.74	1.00	41.36
11	4	78.40	0.09	134.55

A. ALOHA protocol in LoRaWAN

LoRaWAN MAC is based on pure ALOHA protocol. It is asynchronous ALOHA, in which a node wakes up and sends data regardless of any channel sensing or synchronization with the gateway, making it vulnerable to collisions. If any collision occurs, the node has to re-transmit the data, thereby decreasing the channel capacity and consuming more energy. Using pure ALOHA, the nodes can achieve maximum throughput of 18% of the channel capacity, if all nodes in the network are using same parameters [5].

LoRaWAN gets channel diversity by using different parameters, i.e., frequency, SF, BW and CR. This is achieved by using different combinations of these parameters which are orthogonal to one another. Increase in number of end nodes enhances the possibility of two nodes selecting non-orthogonal parameters, hence results in collision. While using 1000 end nodes per gateway LoRaWAN losses are upto 32%, whereas pure ALOHA will have 90% losses in similar case [7].

B. Chanel Activity Detection (CAD)

CAD is a process to detect a LoRa signal, as LoRa signals are mostly below noise floor which make them hard to detect.

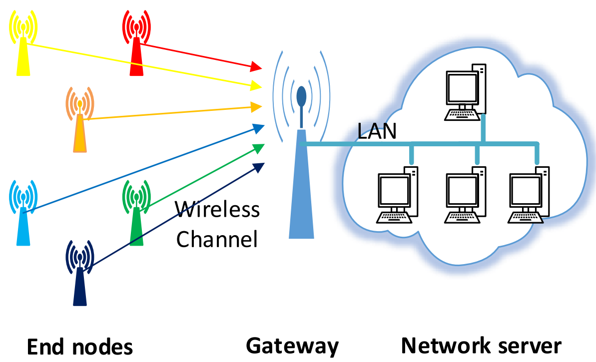

Fig. 1: Network structure

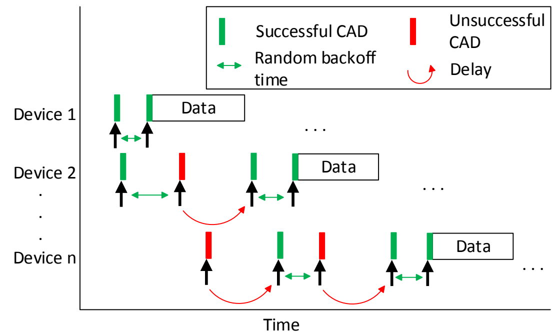

Fig. 2: Principle of LoRa-BED using n number of devices

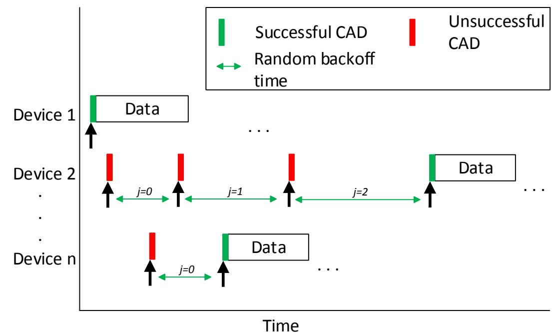

Fig. 3: Principle of LoRa-BEB using n number of devices

After activating *CAD* mode, the device receiver scans the channel depending upon the duration of time provided. If it senses the activity on that channel, i.e., capture of symbols which are correlated successfully, it gives an interrupt with the *ChannelActivityDetected* flag.

It is very important to keep the settings correct to rule out false detection during CAD. Semtech evaluated the performance of *CAD* using SX1261/2 node [14]. They have provided the optimal settings for different *SF* and *BW* as shown in Table II. Furthermore detection of single LoRa symbol is not effective, as false detection rate is very high. Also performing multiple *CAD* for single LoRa symbol do not yield good results. Therefore, we need to detect more than one LoRa symbol to make *CAD* reliable. They also have shown that by detecting two symbols for *SF* 7, 8 and four symbols for *SF* 9-11 using *BW* 125 KHz, the false detection rate remain less than 2%, thus making *CAD* much efficient. Whereas, by detecting more symbols, more energy is consumed. Therefore, energy considerations should be taken into account.

III. Proposed Channel Access Approach

The scope of our design is to make a compatible protocol for LoRaWAN, related to, distributed coordination function (DCF) [15] from where we will adopt binary exponential back-off (BEB) algorithm into LoRa. We consider N number of nodes connected to a gateway. The nodes are randomly distributed around gateway with wireless channel between them as shown in Figure 1. The main goal is to avoid the collisions which happen when LoRaWAN nodes select settings that are not orthogonal to each other. Therefore, we need LBT mechanism to minimize the loss of transmitted data. The functionality of our proposed protocol can be summarize as

- Sensing channel using *CAD* method to find if the channel is idle or not.
- If channel is busy, the algorithm will find how much it should wait to sense channel again.
- If channel is idle, the algorithm will find when the node should transmit data.

The proposed algorithm runs on end nodes, calculating the time when node should transmit its data with respect to the channel condition.

Following are the assumptions we make while designing the protocol.

- All nodes are considered to be stationary and spread equally around the gateway.
- Path loss is ignored, which implies that gateway will receive every packet above its sensitivity level.
- There is only up-link (*UL*) traffic, i.e., gateway is not sending acknowledgements to the nodes.
- Hidden nodes are ignored. All nodes are considered to know the channel conditions by using CAD.
- All nodes are assumed to use same settings, i.e., same frequency, channel, SF, BW and CR. This is to ensure a collision based environment to check the performance of the proposed protocol.

A. LoRa-BED

In LoRa-BED, we use binary exponential delay (BED) technique. If node n wants to transmit the data, first it will start *CAD* process on the channel and wait till T_{CAD} i.e., wait for *ChannelActivityDetected* flag interrupt. T_{CAD} value is given in Table II for different SFs. If the flag interrupts in selected T_{CAD} time, it will be called Unsuccessful *CAD* (*UC*), which implies a busy channel. If interrupt does not occur in T_{CAD} time, it will be called Successful *CAD* (*SC*), which means channel is idle. If the channel is busy, the node goes into delay state, where it defers the transmission for time D_{CAD} (Delay) which is exponentially decreasing with increasing number of

Algorithm 1: Pseudo code of operation on end node using LoRa-BED, LoRa-BEB and LoRa-BEH as mode 1, mode 2 and mode 3 respectively.

```
Initialize: mode, i_max , T_CAD, ToA_max
fl ← 0, i ← 1, j ← 0, k ← 0
while Data is not transmitted do
    Start CAD
    Wait T_CAD milliseconds
    if Channel is idle and (fl = 1 or mode = 2) then
        Start transmitting data
    else if Channel is idle and fl = 0 and mode ≠ 2 then
        if mode = 1 then
            T_RB ← randi[0, ToA_max]
        else if mode = 3 then
            T_RB ← randi[0, (2^k) ToA_max]
            k ← k + 1
        Wait T_RB milliseconds
        fl ← 1, i ← 1
    else if Channel is busy and mode = 2 then
        T_RB ← randi[0, (2^j) ToA_max]
        Wait T_RB milliseconds
        j ← j + 1
    else
        D_CAD ← (2^-i) ToA_max
        Wait D_CAD milliseconds
        if i < i_max then
            i ← i + 1
        fl ← 0
```

UC. For every *UC*, D_{CAD} is calculated using equation given below, until the channel becomes idle again,

$$D_{\text{CAD}} = (2^{-i})ToA_{\max}, \tag{5}$$

where i is a counter which increases by one for every consecutive *UC* and it resets when channel is found to be idle. The counter i has maximum limit of 7, such that the minimum delay time $D_{\text{CAD}_{min}}$ with $i_{\max}$ is greater than T_{CAD}, to give the node enough time to perform *CAD*. If channel is idle, then the node goes into back-off state where the node selects its back-off time, T_{RB}, randomly from [0, $ToA_{\max}$], before getting into transmission state. It is necessary to include a random back-off time to prevent the nodes sending data at the same time instant, which then results in collusion between the data packets. The proposed approach is shown in Figure 2.

B. LoRa-BEB

This protocol is based on binary exponential back-off (BEB), similar as in DCF in which window size (W) increases exponentially with every collision. In $LoRa-BEB$ we increase the W exponentially with every *UC*. Whenever node n wants to send data and channel is busy, the node goes directly into back-off state, in which it selects T_{RB} randomly from [0,W], where W can be calculated as,

$$W = (2^j)ToA_{\max}, \tag{6}$$

where j is counter which starts from zero and increases by one for every *UC*, it will not reset unless the node sends the packet. As it can be seen in Figure 3, after first *UC* the value of j starts from 0 and it increases for every *UC*. If channel is found to be idle, the data is transmitted instantly without any wait.

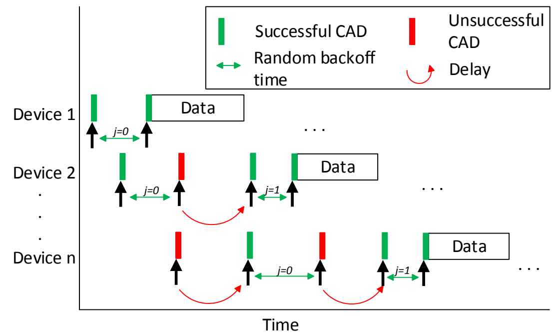

Fig. 4: Principle of LoRa-BEH using n number of devices

TABLE III: Simulation parameters used to obtain results

Parameter	Value
Simulation interval	1 hour
PL	5-255 Bytes
n_p	8 Symbols
SF	11
BW	125 KHz
CAD time	78.40ms
DE	1
H	0
CRC	1

C. LoRa-BEH

LoRa-BEH (binary exponential hybrid) is the combination of both BEB and BED techniques. Whenever node finds busy channel, it will go into delay state for the time D_{CAD} (Equation 5) and stays in this state until it finds idle channel. If node finds idle channel, it will go into back-off state where it will back-off for time T_{RB} randomly from $[0,W]$ and W is calculated using Equation 6. After T_{RB}, if the node finds the channel to be idle it will go into transmission state and will transmit instantly, otherwise it will go again into delay state as shown in Figure 4. Algorithm 1 presents the pseudo-code running on each end node using one of the above three methods.

IV. Results and System Performance

The results have been obtained by MATLAB simulations using the parameters specified in Table III, as payload size of the packet is variable and randomly chosen from specified

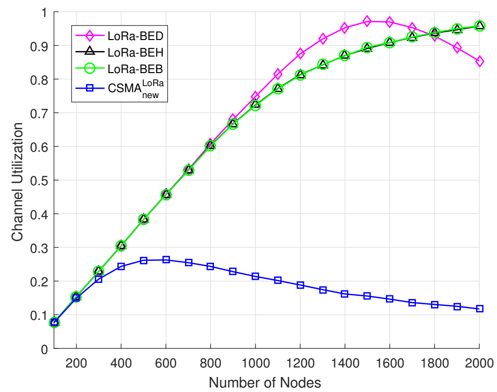

Fig. 5: Channel utilization vs. number of nodes for $LoRa-BED$, $LoRa-BEH$ and $LoRa-BEB$ with comparison to $CSMA^{LoRa}_{new}$ [12]

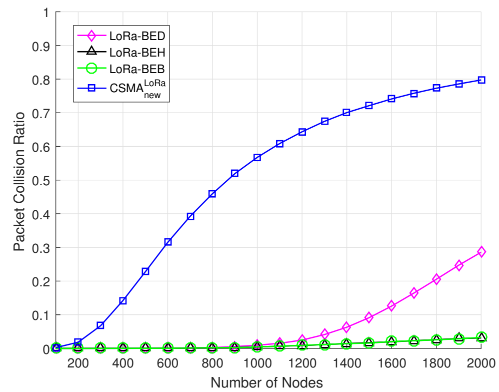

Fig. 7: Packet collision ratio vs. number of nodes for $LoRa-BED$, $LoRa-BEH$ and $LoRa-BEB$ with comparison to $CSMA^{LoRa}_{new}$ [12]

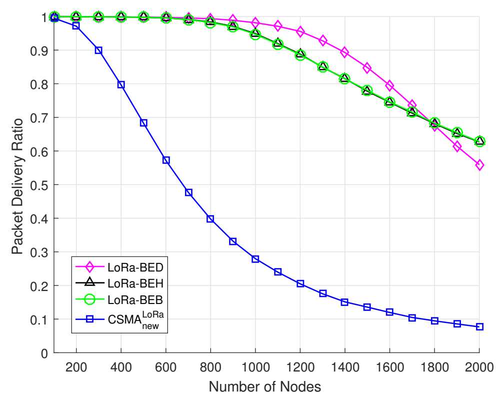

Fig. 6: Packet delivery ratio vs. number of nodes for $LoRa-BED$, $LoRa-BEH$ and $LoRa-BEB$ with comparison to $CSMA^{LoRa}_{new}$ [12]

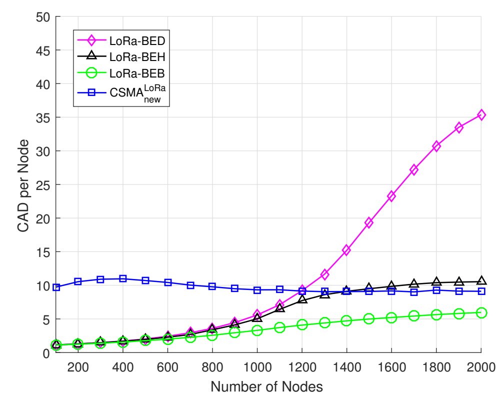

Fig. 8: CAD per device vs. number of nodes for $LoRa-BED$, $LoRa-BEH$ and $LoRa-BEB$ with comparison to $CSMA^{LoRa}_{new}$ [12]

values. CAD time is taken from Table II for SF 11 using 4 symbols, which is the most reliable CAD among all. Every node chooses its random packet sending time, P_t, from the interval of an hour. Each node will send only one packet in the above defined interval without any retry, if collided. A packet is assumed collided if some node starts transmitting in between the CAD time of other node. Channel load is measured as the number of nodes that want to send data within T_s. If we increase number of nodes, channel load also increases. We have shown the results for channel load less than 1%.

Figure 5 shows the channel utilization which is seen to be reaching up-to 95% for all three proposed approaches. We see that LoRa-BED increases more abruptly than the other two approaches and then starts to decline due to collision as the channel load increases. This shows that LoRa-BED utilizes channel better for less number of nodes whereas LoRa-BEB and LoRa-BEH work better for greater number of nodes. Figure 6 shows the number of packets delivered in an hour for every protocol by increasing the number of nodes. All curves starts to drop after specific number of nodes because of reaching saturation point of maximum packets that can be send per hour.

Figure 7 shows that LoRa-BED is more prone to collisions as the number of nodes surpasses 1000, and with 2000 nodes the packet loss reaches around 30%. Whereas, other two proposed protocols have very gradual increase in the number of collisions and with same number of nodes, the loss is only around 3% and 2% for LoRa-BEH and LoRa-BEB, respectively. Figure 8 shows energy perspective of all the protocols, where LoRa-BEB is using least amount of CAD per node with respect to others as more number of CAD consumes more energy. With 2000 nodes LoRa-BEB needs on average of 6 CAD per node. Energy consumption per CAD is shown in Table II for SF 11.

V. Conclusions

In this paper, we investigated how LBT can be adopted in LoRaWAN. We investigated the best settings for CAD channel sensing technique for which it has maximum reliability. We proposed three channel access protocols using novel channel access techniques which can be adopted in LoRaWAN. As a result we showed an improve in channel utilization and decrease in number of collisions with little increase in energy while sensing the channel. More importantly, LoRa-BEB has excelled among all the proposed solutions with having minimum energy usage (CAD per device) and less number of collisions.

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