Development and analysis of new implementations of MAC proto-cols and mobility models in LoRa networks

Desenvolvimento e análise de novas implementações de protótipos de MAC e modelos de mobilidade em redes LoRa

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ABSTRACT
The technological revolution known as Internet of Things (IoT) brings together several areas of science and technology, such as data acquisition, energy consumption, Wireless Sensor Networks (WSN), data analyses and processing among others. IoT gets its name from the several applications, from wearables to cars connected to the network, spanning the transportation, health, electronics, water, and electricity industries. This massive addition of LoRa devices for its own application brings the problems of a shared medium such as frame collision. Additionally, as the devices are often battery powered there is a need to analyze the battery consumption. It was found that there is a lack of tools to estimate the consumption and performance of a network. In this paper, we implement new medium access control mechanisms for LoRaSim simulator, based on CSMA/CAD (Carrier Sense Multiple Access with Collision Avoidance and Detection). This addition tests the influence a different access protocol has on the LoRa network and its resilience. As part of this study the new access protocol is built on the existing simulator LoRaSim to study the difference between the access protocol currently used in LoRa, an ALOHA protocol variant, CSMA/CA (CSMA with Collision Avoidance) and CSMA/CAD with the purpose of analyzing the difference in collision between protocols and the respective energy consumption in mobility scenarios.

Keywords: LoRaSim, collision ratio, CSMA/CA, CSMS/CAD, simulation, LoRa, energy consumption, mobility.

RESUMO
A revolução tecnológica conhecida como Internet das Coisas (IoT) reúne várias áreas da ciência e tecnologia, tais como aquisição de dados, consumo de energia, redes de sensores sem fio (WSN), análise e processamento de dados, entre outras. A IoT recebe seu nome das diversas aplicações, desde produtos de desgaste até carros conectados à rede, abrangendo as indústrias de transporte, saúde, eletrônica, água e eletricidade. Esta adição massiva de dispositivos LoRa para sua própria aplicação traz os problemas de um meio compartilhado, como a colisão de estruturas. Além disso, como os dispositivos são freqüentemente alimentados por bateria, há a necessidade de analisar o consumo da bateria. Descobriu-se que há uma falta de ferramentas para estimar o consumo e o desempenho de uma rede. Neste artigo, implementamos novos mecanismos de controle de acesso ao meio para o simulador LoRaSim, baseado no CSMA/CAD (Carrier Sense Multiple Access with Collision Avoidance and Detection). Esta adição testa a influência de um protocolo de acesso diferente sobre a rede LoRa e sua resiliência. Como parte deste estudo o novo protocolo de acesso é construído sobre o simulador LoRaSim existente para estudar a diferença entre o protocolo de acesso atualmente usado no LoRa, uma variante do protocolo ALOHA, CSMA/CA (CSMA with Collision Avoidance) e CSMA/CAD com o objetivo de analisar a diferença de colisão entre protocolos e o respectivo consumo de energia em cenários de mobilidade.

Palavras-chave: LoRaSim, taxa de colisão, CSMA/CA, CSMS/CAD, simulação, LoRa, consumo de energia, mobilidade.

1 INTRODUCTION

Currently IoT is spread across all areas and sectors, providing a bigger control over day-to-day operations, or helping companies develop with the data acquired through these types of networks.

The Long Range (LoRa) [1] and Low Power (LP) networks used in IoT applications have a wide variety of uses, from controlling the pollution in a city to the measurement of moisture in the soil, it allows the deployment of use cases that would be impossible when using traditional network solutions [2].

The fact that these devices can have a lifespan of years running off batteries and a small size, allows them to be designed with mobility in mind. This factor coupled with the mass implementation of IoT networks, and its devices brings the problem of a shared medium, collisions. Frame collision is affected by traffic characteristics such as frequency, transmission length and payload [3].

The aim of this paper is to continue the work developed in [4] and study the implementation of CSMA/CA [5] and CSMA/CAD [6] in the LoRaSim simulator [7] – one of the most popular simulators for LoRa/LoRaWAN – and analyze the impact between Medium Access Control (MAC) protocols and frame collision data and look also for the energy performance of the MAC protocols. The study and analysis of the performance of the frame collisions according to the different MAC protocols: ALOHA [8], CSMA/CA and CSMA/CAD could be a very interesting point to study other communications aspects in LoRa/LoRaWAN, such as the mobility of the devices and network planning.

This article begins by giving a brief introduction into LoRa and LoraWAN in section 2 and goes on to explain the LoRa modulation in section 3. Section 4 talks about the mobility model used in the simulation and section 5 exposes the random-access techniques used in IoT and section 6 explains the simulation environment. In section 7 the results are presented and in section 8 is the conclusion and some remarks for future work.

2 LORA MODULATION

LoRa (Long Range modulation) [1] [9] e is a proprietary spread spectrum modulation technique based of Chirp Spread Spectrum (CSS) modulation that makes it robust to noise, increases range and has a low energy consumption. This modulation trades bit rate for sensibility. This technology is a physical implementation and agnostic to higher layers which allows for coexistence with the existing network architectures.

The modulation can be characterized by a couple key factors like Bandwidth (BW), Carrying Frequency (CF), Code Rate (CR), Spreading Factor (SF) and transmission power.

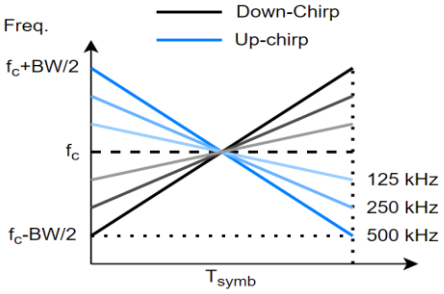
The LoRa wireless communication in the European Union operates in the 868 MHz frequency and has a configurable BW, this band is in an unlicensed spectrum. The CR defines the Forward Error Correction (FEC) that is used to protect against errors, it can be configured as 4/5 that adds one extra parity bit for each 4 bit of information to a maximum of 4/8 that doubles the information sent but provides good protection against errors. The SF is the number of bits per encoded symbol, it influences the data rate, time on air and receiver sensibility.

2.1 SPREAD SPECTRUM COMMUNICATIONS

LoRa is based on the CSS modulation scheme [9] where the use of a Compressed High Intensity Radar Pulse (Chirp) that sweeps the frequency, un increase in frequency is called an upchirp and a decrease in frequency is called a downchirp.

A Chirp can start in a random position and when it reaches its maximum in f_c + *BW/2* the frequency goes back to the minimum at f_c - *BW/2*, see Fig.1.

Fig. 1. Spectrogram representation: Up-chirp and Downchirp



The standard defines the LoRa preamble as six upchirps and two downchirps. An increase in BW also increases transmission speed and reduces the channel occupation but sacrifices receiving sensibility.

Another parameter of great importance in LoRa modulation, is the SF that can go from 7 to 12 depending on the conditions in which the transmission is being made. It is important to adapt the SF to the scenario as a low SF like 7 means that more chirps are being sent per second, thus more information can be coded per second however the range of the transmission is diminished. On the other hand, a SF of 12 provides better range but the chirps are more spread out in time.

The symbol period, T_S, can be defined by (1)

$$T_s = \frac{2^{SF}}{BW}[\text{sec}] \quad (1)$$

Where SF is the spreading factor ranging from 7 to 12, BW the bandwidth and CR the coding rate [9].

To measure the device energy consumption, we followed the implementation in [10]. Where they implement the energy consumption as the sum of the energy spent on each phase: transmission, reception and idle.

$$E = E_{tx} + E_{rx} + E_s \qquad (2)$$

$$E = T_{tx}P_{tx} + T_{rx}P_{rx} + T_sP_s \qquad (3)$$

Furthermore, we can divide the energy spent by the device into time of transmission and the consumption of the activity it is performing, where T_{tx} is the amount of time the device is transmitting data and P_{tx} is the consumption of the device. Utilizing the same methods for the receiving and sleeping parameters we can get an approximation of the device consumption.

The following code represents the energy calculations added to the simulator. It is measured in [10] that a device running the Semtech SX1272 chip consumes 40 µA in sleep mode and 10 mA in receive mode. As the simulator already had a table for the transmission power that table is used and has a range from -2 to +17 dBm.

AvgenergyRx = (sum(node.packet[0].rxtime*10*node.sent* V for node in nodes)/1e6)/len(nodes)

AvgenergyTx = (sum(node.packet[0].rectime * TX[int(node.packet[0].txpow)+2] * V * node.sent for node in nodes) /1e6)/len(nodes)

AvgenergySlp = (sum(node.packet[0].slp*0.04 * node.sent *V for node in nodes)/1e6)/len(nodes)

The operations executed by the device can be all classified with one of the states. The program stores all interactions with a gateway in the variable node, it also stores some pertinent information for further analysis, such as the time-on-air of the packets in rectime, the transmission time for 12.5 simbols in rxtime and the number of packets sent in sent.

Taking some of Semtech datasheets for device consumptions and other studies in the area [11] [12]. We can estimate the consumption a device has in any give state.

The energy factor is especially important because most LoRa devices operate with only a battery. This means that collisions are fatal to them as it correlates to loss of energy, network efficiency and battery life.

We aim to test if the consumption of slightly more efficient protocols like CSMA/CA and the new CSMA/CAD provide any benefit to the network and its energy consumption.

2.2 LORAWAN

The LoRaWAN specification was created and is currently kept by the LoRa Alliance^{TM} [1] that regulates the use of the LoRa technology in the unlicensed frequency band IMS [13] and acts as a MAC protocol but acts mainly as a network protocol.

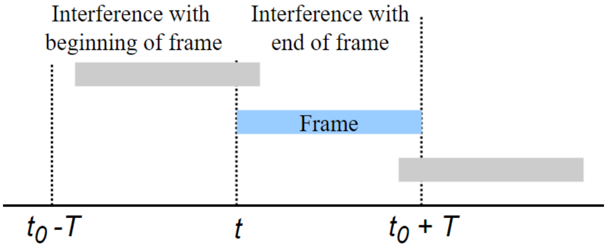
The specification defines three classes for the devices, named: Class A, B and C. Each class represents a different mode of operation, each one with its advantages and disadvantages. Class A supports the basic operation as well as bidirectional communication and is mandatory in all devices. The devices use an ALOHA-like protocol (as a MAC protocol) for transmitting and set up two receive windows. This class is the most energy efficient and is the one we study in this paper. Class B implements bidirectional communication with scheduled downlink slots. To keep the devices in sync the gateway sends information through beacons. Class C has the same uplink schedule as Class A but keeps the receiving window always open providing less latency but more energy consumption.

3 RANDOM ACCESS CHANNEL TECHNIQUES IN IOT

Frame collision is a constant problem in any kind of network wireless and wired. In a wireless scenario the medium is shared and makes controlling and coordinating information exchange difficult. Each device is competing for the use of the receiving node. If two devices transmit at the same time a collision occurs and both frames are rejected.

In LoRaWAN the technique used by Class A devices is a slotted ALOHA-like protocol that lacks collision prevention techniques. This protocol operates on the basis that if a device has information to be delivered it will be sent and after the transmission is complete, the device waits a predetermined amount of time defined in the LoRaWAN specification before opening the reception window to accept data sent by the gateway usually an acknowledgement (ACK). Fig. 2 represents an example of the functioning of the ALOHA access protocol and some of the problems that come with it.

Fig. 2. – ALOHA Technique

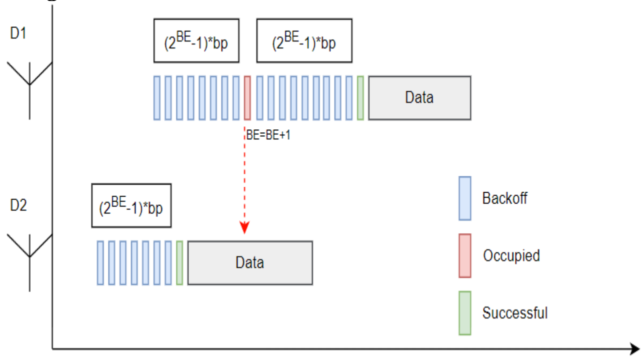


In LoRaSim this collision checking is done by doing a collision check in frequency and SF as the frame is still salvageable if either of those values is different. For a more in-depth collision checking timing and power are also checked as the transmission succeeds if at least 5 preamble symbols are received. In the power domain if the stronger signal overpowers the weaker one, usually this threshold is a 6 dB difference.

The problem with using ALOHA in busy networks is the fact that devices will not check the medium for other transmissions, and the network will be overwhelmed. To prevent this a good alternative could be the CSMA/CA protocol in the MAC layer. Collision Avoidance is an improvement over the traditional CSMA and attempts to improve the performance of channel access by the devices. In this protocol before any transmission the device checks the medium to see if it is free, in the event a carrier is detected the device waits a random amount of time, known as backoff counter before checking the channel again.

The IEEE 802.15.4 standard [13] defines the operation of low-rate wireless personal area network (LR-WPAN) and specifies the physical and MAC layers. This standard introduces two modes a beaconless mode with unslotted CSMA/CA and a slotted CSMA/CA with a beacon. The beacon mode requires a high-level coordinator that provides beacon-related information and marks the start of a super frame. This mode requires the device to listen for the beacon and wait the beginning of the super frame. In this paper we focus on the analysis of the beacon-less mode seen in Fig. 3.

Fig. 3. IEEE 802.15.4 non-beacon unslotted CSMA/CA



In beaconless mode the device waits a random number of backoff periods between $[0,2^{BE}-1]$. If at the end of the waiting period, the channel is in idle the transmission begins, if it is busy with a transmission the device waits an additional waiting period.

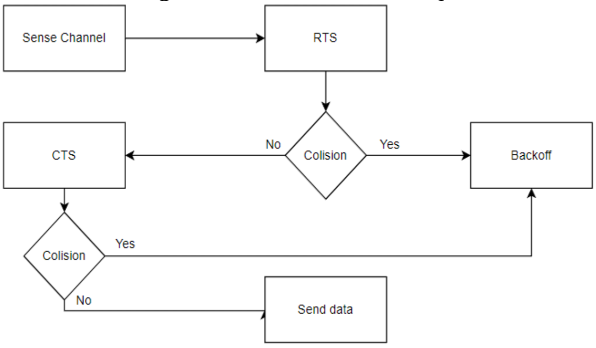
The following code represents the CSMA/CA implementation added to LoRaSim, a backoff time counter, botcounter, is added and collisions are checked every time the backoff counter finishes with the yield function, if the channel is idle, it exits the loop and the transmission is done, if the channel is busy, it generates a new backoff time and waits again to a maximum of 5 times.

```
botcounter=0
for botcounter in range(5):
node.packet[bs].addTime = env.now
if (checkcollision(node.packet[bs])==1):
node.packet[bs].rxtime =node.packet[bs].rxtime+Rx
rndm_TCol=random.randrange(5, 400, 1)
node.packet[bs].slp = node.packet[bs].slp
+ rndm_TCol
yield env.timeout(rndm_TCol)
else:
break
```

Another approach is CSMA/CAD the addition this technique makes is the integration with CSMA/CD. As radio interfaces are half-duplex, where a transceiver desensitizes the receiver module during a transmission CSMA/CD has been hard to implement. CSMA/CD detects a collision when during transmission the device receives a frame in which case the transmission is halted, and the device waits a random amount of time.

CSMA/CAD [6] attempts to bring both the CSMA implementations together. Before sending a Request-to-Send (RTS) the device uses carrier sense and when transmitting a RTS and a Clear-to-Send (CTS) it uses collision detection. If the device detects activity in the medium before a RTS is sent or during the RTS, CTS detects a collision the device backs off and terminates the current transmission. A successful transfer is made once both CTS and the ACK are received. The advantage this model has is the fact that a device does not need to finish the transmission of RTS or the listening of the CTS due to the collision detection feature, saving battery by avoiding unnecessary transmission or listening time.

Fig. 4. CSMA/CAD Technique



4 MOBILITY MODEL

In order to access the mobility of a device a model that replicates the movement patterns of a person or a device. These models include random movement models (random walk, random way point, random direction), special correlation (pursue mobility, column mobility) and temporal correlation (Gauss-Markov, Levy flight).

The precision of mobility models can be measured by their proximity to realistic mobility patterns. However, the amount of precision a model has is related its computational cost or mathematical complexity.

In the individual mobility models with memory or temporal dependency, the user continues its movement independently from other devices, but is influenced by its previous position and speed.

The Gauss-Markov mobility model was originally proposed in [15] and used for the simulation of an ad-hoc network [16]. In this model it is initially given a direction and velocity to each node. And after a fixed amount of time, n, the movement occurs by changing the speed and direction.

$$s_n = \alpha s_{n-1} + (1-\alpha)\bar{s} + \sqrt{(1-\alpha^2)}s_{x_{n-1}} \quad (4)$$

$$d_n = \alpha d_{n-1} + (1-\alpha)\bar{d} + \sqrt{(1-\alpha^2)}d_{x_{n-1}} \quad (5)$$

Where sn and dn are the new values of speed and direction for the node in the new time slot n, and α is the turning rate, where $0 \leq \alpha \leq 1$. $\bar{s}$ and $\bar{d}$ are constants representing the average speed and direction, $s_{x_{n-1}}$ and $d_{x_{n-1}}$are random variables with a gaussian distribution. In the following piece of code, it is shown the implementation of equation 4 and 5 for the speed and direction respectively.

```
node.vel = (alpha * node.vel +
alpha2 * velocity_mean +
alpha3 * np.random.normal(0.0,1.0))

node.dir = (alpha * node.dir +
alpha2 * node.mean_dir +
alpha3 * np.random.normal(0.0,1.0))

Xn = node.x + node.vel * np.cos(node.dir)
Yn = node.y + node.vel * np.sin(node.dir)
```

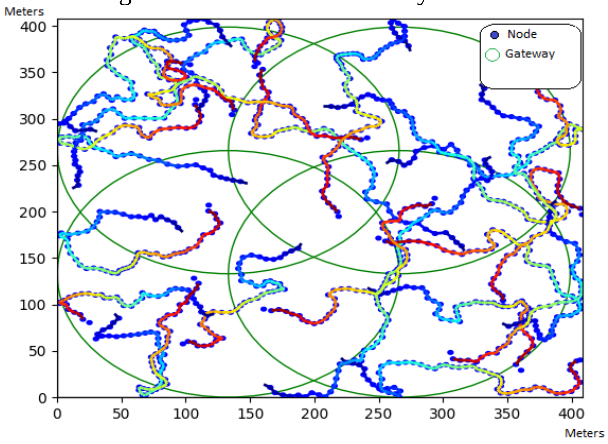
At the end of a time slot the next location is calculated with the current position, velocity, and direction in mind.

$$x_n = x_{n-1} + s_{n-1} cos\, d_{n-1} \qquad (6)$$

$$y_n = y_{n-1} + s_{n-1} sin\, d_{n-1} \qquad (7)$$

Where (x_n, y_n) and (x_{n-1}, y_{n-1}) are the coordinates of the node in n and n-1, s_{n-1} and d_{n-1} are the previous speed and direction for the node. Equation 6 and 7 are the last two lines of the previous code.

Fig. 5. Gauss-Markov Mobility Model

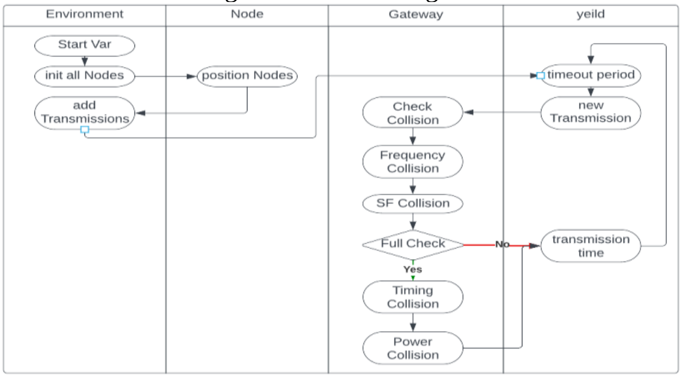


In Fig. 5. it is possible to observe the movement pattern of a node as time progresses.

5 USING LORASIM

The simulator chosen to emulate LoRa communications was LoRaSim [7]. Developed in the university of Lancaster the simulator uses Python to and the Simpy module to create a discrete simulation environment that allows us to create any number of devices and gateways and observe the throughput of the network.

Fig. 6. LoRaSim Diagram



This simulator only has the basic ALOHA protocol implemented and to test the channel access techniques new additions were done to the existing simulator to implement the addition of CSMA/CA and CSMA/CAD.

5.1 SIMULATION SETTINGS

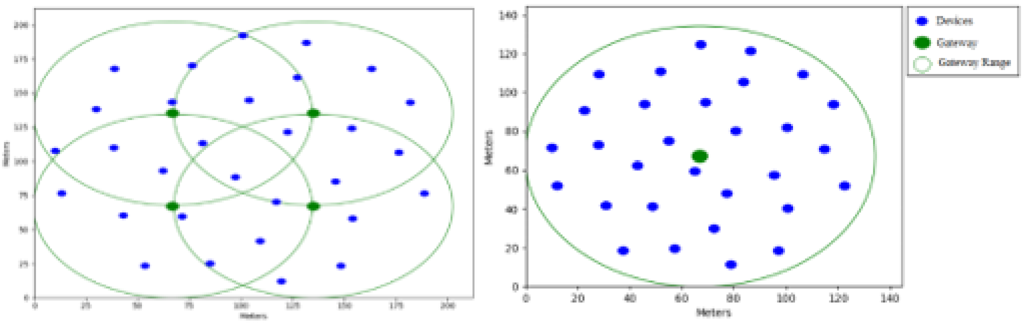
Table 1. Simulation Parameters

Voltage	3.3 V
Frequency	868 MHz
Code Rate	4/5
Bandwidth	125 kHz
Output Power	2-14 dBm
Payload Length	20
Preamble Length	12.5 Symbols
Spreading Factor	SF7 /SF12

The tested scenario was simple with one to four gateways and the number of devices varying from 1 to 500. The distance at which the devices were deployed was dependent on several key factors and standard LoRa modulation parameters. Namely the transmission power and the SF.

To ensure the devices stayed in the same position and the results weren't affected by the random distribution of nodes it was opted to implement a sunflower pattern distribution. Although not a realistic setting our purpose is to analyze the difference between the different MAC protocols and this distribution allows the devices to be evenly distributed between the gateways and make the testing more uniform, see Fig. 7.

Fig. 7. Gateway and Node Distribution for 1 and 4 Basestations



The LoRaSim tool comes with ALOHA implemented and the possibility of adding other access protocols makes it a good developing tool. Table 1 presents the parameters the simulation was running. We considered several scenarios, with 4 gateways and devices ranging from 1 to 30 devices.

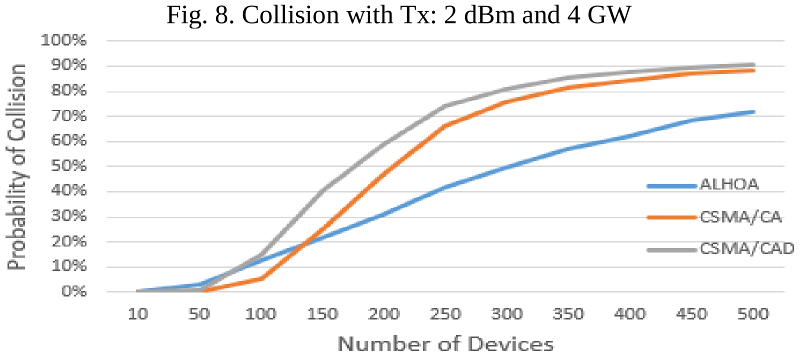
To improve LoRa with other modulation protocols and see if the rate of collisions could be improved, we started by adding the principle of the CSMA protocol. To implement it a sensing mechanism must be implemented so that it can check the medium before it accesses and starts transmitting data. As previously mentioned in CSMA/CA before any transmission the device checks the medium to see if it is free and if it detects it is being used it backs off and waits a random amount of time. If it is free, it starts transmitting the data. To implement this before any transmission the simulation will run the collision checking functions and report if any collision is bound to happen if it returns positive that a collision will indeed happen it backs off for a random amount of time at the end of the backoff period it checks the medium again to see if its free and repeats the process.

Another technology that was implemented was the CSMA/CAD. This variation of the access protocol is intended to ensure all data packets and ACKs are delivered without collisions. This involves the use of the RTS and CTS package, and if this exchange succeeds the packet is sent. This protocol combines the two CSMA technologies: the collision avoidance is used before sending the RTS packet to ensure the channel is clear, and the collision detection is used during the CTS window if any of these steps detects a collision the transmission is aborted and a backoff time is engaged and at the end the process is restarted.

6 SIMULATION RESULT

After implementing the functioning of the three protocols they were put through some tests to see if the protocols provide an increase in reliability.

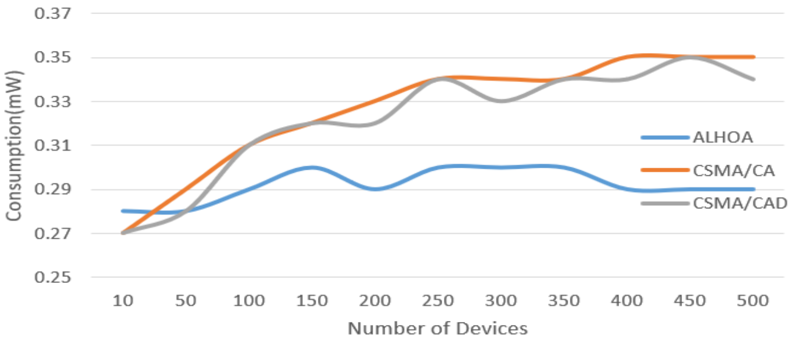
Fig. 8. Collision with Tx: 2 dBm and 4 GW



In Fig. 8 a four gateway test was made to see the performance of the protocols when the devices are transmitting at the lowest transmission power, and we can see the collision probability of protocols with medium access control like the CSMA/CA or CSMA/CAD tend to a logarithmic shape while ALOHA shows a steady increase. It is also possible to see the improvement of the CSMA/CAD over the regular CA version.

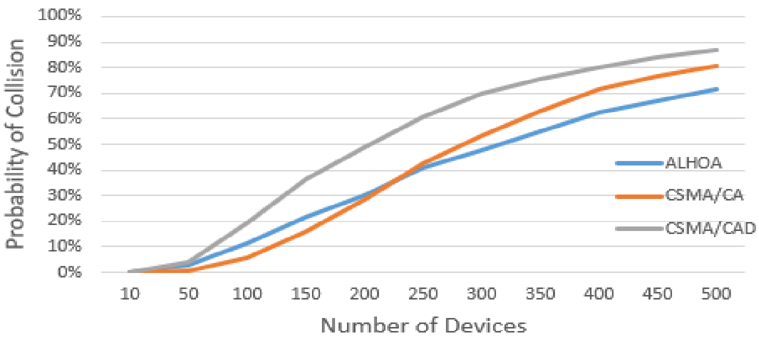
From Fig. 9 we can see the increase in energy a technique like CSMA/CA and CSMA/CAD adds to the normal used by ALOHA, CSMA/CAD drops off in the Consumption due to its operating nature.

Fig. 9. Protocol Energy Consumption for 2 dBm



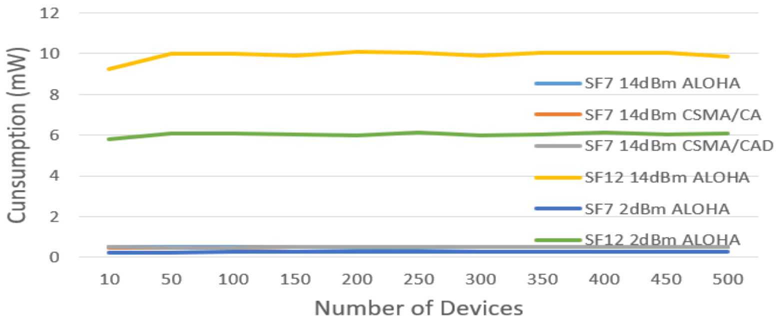
In Fig. 10 we can see the collision for the SF12 is lower than in Fig. 8 with SF7, and it is to be expected since the time on air is bigger and the time between transmission and retransmissions increases. The ALOHA protocol has a higher chance of a collision than CSMA/CA and CSMA/CAD.

Fig. 10. Collision Probability with SF12



In Fig. 11 we can see the several energy consumptions of a device depending on the parameters they have. One important take away is that the increase in energy consumption depending on what LoRa component is changed. We can observe that an increase in transmission power does not increase consumption as much as an increase in SF being SF12 the most expensive of them all due to the low data rate that makes it occupy the medium for a longer period.

Fig. 11. Consumption Evaluation in ALOHA protocol



After the implementation of the Gauss-Markov mobility protocol the first test has a SF7 for the increased bit rate and transmission speed. In Fig.12 we can see the collision probability increasing with the number of nodes. However, like in Fig. 8 the CSMA algorithms have a logarithmic behavior while the ALOHA protocol steadily increases.

Fig. 12. Gauss-Markov SF7

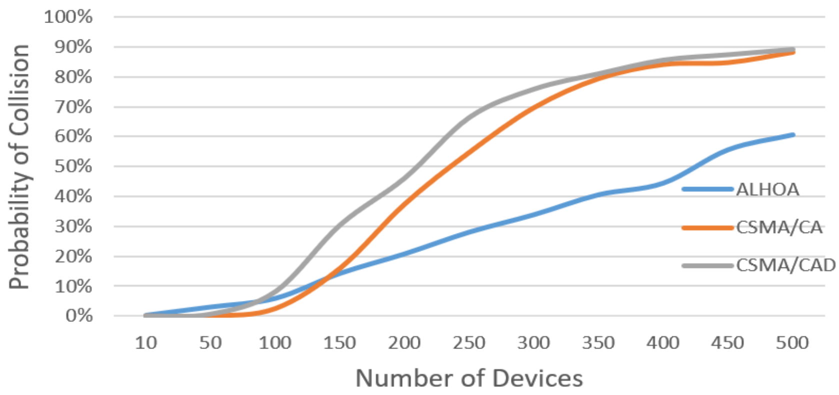
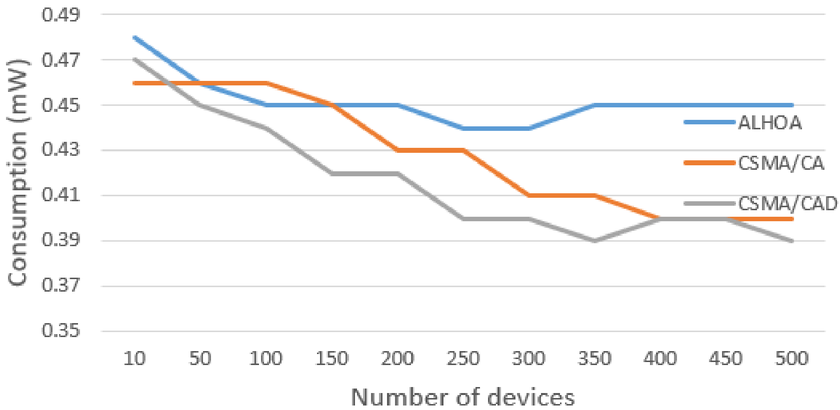


Fig. 13. SF7 Simulation Energy consumption



In Fig.13 it is possible to see that the energy consumption during the simulation time for several scenarios with the only change being the access protocol.

As the number of devices rise the energy consumption of the ALOHA protocol isn’t affected as it doesn’t check the medium before data is sent.

In the CSMA/CA and CSMA/CAD it is possible to see a decrease in energy consumption with the increase of the number of devices. And this shows the effect access control has over the energy consumption of devices in the most saturated networks.

7 CONCLUSION AND FUTURE WORK

This paper provides an analysis on alternative protocols to ALOHA and to be used in LoRa networks is a valid concern as the massive adoption of IoT causes the use of networks to be more populated and increases the collision and energy use in the network. The advantage of studying these protocols in a simulator is its low cost, as there isn’t a need for physical devices and allows us the freedom to try scenarios that weren’t possible otherwise. LoRaSim also allows for the addition of new modules, like what was done in this paper due to its implementation of basic LoRa communication. Algorithms such as CSMA/CA and CSMA/CAD were created and implemented so that a comparison could be made between ALOHA, CSMA/CA and CSMA/CAD. As expected, the performance of the ALOHA protocol struggles to keep up with the increase of devices in a network having CSMA/CA succeed in having a better performance in terms of collisions. The slight increase in energy is acceptable depending on the need for expansion in networks as the benefits of using other access protocols only come with the chance to add more devices to the network.

A Mobility model with temporal correlation was also implemented to observe the performance of these new protocols with the mobility devices.

As more and more IoT devices are battery powered they can now be used for less static applications allowing movement which leads to a different approach in the design networks and devices as well as their number. This creates an additional level of complexity that influences the network performance and contributes to the frame collision, making the study of device mobility applied to these networks an interesting topic that should be delved further.

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