

SenseNet: IoT Temperature Measurement in Railway Networks for Intelligent Transport

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Abstract— *Wireless sensor networks have become an attractive choice for many monitoring applications in unattended setups such as railway lines and highway monitoring; hence, which requires optimized sensor placement in a linear topology for effective optimum coverage. These sensors need to be placed as far apart while still maintaining a minimum required coverage in order to minimize the required node count and reduce cost. The objective of this paper is to strategically place sensors in order to determine the minimum number of sensors and their locations, such that every grid point is covered with a minimum confidence level. We experimented and evaluated the number of nodes and packet rate variation on the performance of different MAC protocols over the deployment of wireless sensor networks on the “Train Express Region” (TER) of the Dakar region in Senegal.*

Keywords—Coverage, Optimization, Sensor, Protocol

I. INTRODUCTION

Since advances in structural engineering depend largely upon the availability of monitoring techniques as a response mechanism to diverse structural excitation of abnormal circumstances, a continuous growing demand for structural monitoring and performance assessment has been a growing concern with challenges in the design of optimal wireless sensor networks with cost effective performance. In our study, we used the Dakar ‘Train Express Region’ (TER) rail network as our test-bed for an optimal deployment of wireless sensor networks for temperature measurement.

With the unprecedented rapid growth of population in Dakar, the use of the ‘Train Express Region’ (TER) trains which shuttles from the suburbs of Dakar to the new airport of (AIBD), has recently attracted more attention because of its large carrying capacity, fast running speed and high transportation efficiency. While the demand of high speed, safety and stability of the TER train also puts forward higher requirements for structural security and performance monitoring, there is need to adopt a technology which is capable of sensing local environmental conditions e.g., temperature and fixed object detection, as well as GPS information, to avoid track failures and derailments along the railway.

With the TER railway network, there exist fourteen train stations and the estimate distance of the train route from its

point of origin to the final destination of the airport spans about 67.7 kilometres in circuitous line. Notwithstanding, the untimely crossing of the train route by the pedestrians, vehicles, and the uncontrolled movement of livestock within the local neighbourhoods can cause a high risk of train obstructions and accidents during movement.

As a result of these challenges for the smooth operation of the trains in the suburbs, we are motivated to deploy an optimized wireless sensor network with maximum coverage, given the location’s many relevant indicators, such as reliable connectivity, energy consumption, bit error rate (BER) and considering the use of various MAC protocols.

The layout of the paper is presented as follows. Section II presents the related work. Section III describes the experimental setup of our architecture. Section IV discusses the evaluation of different MAC Protocol scheme, Section V highlights the simulation method and analyses the achieved results, and Section VI draws the conclusions and possible future work for a more scalable railway monitoring technique.

II. RELATED WORK

A variety of algorithms have been developed to facilitate sensor placement optimization. Kai Zhou *et al* [1] (Zhou, 2017), gives the mathematical formulations of four approaches in the sensor placement framework including modes shape difference (MSD), effective independence (EI), information entropy (IE), and modal energy (ME). The author’s framework enabled an optimized sensor placement solution whose performance enhancement was verified by comparing its performance with that of the instrumented sensor layout provided in a case study. However, the results of their work did not take into effect how terrain effects are modelled by modifying the size of the sensor radius of coverage based on the characteristics of the terrain the sensors are placed on.

The authors of [2] presented extensive real hardware measurements of RSSI: (Received Signal Strength Indication) and compared to the theoretical models, to investigate the IEEE 802.15.4 ZigBee propagation channel characteristics. In their study, they presented results of extensive measurement log frame that validates Log-normal and shadowing path-loss model with accurate loss parameters at 2.4 GHz in outdoor

environments. However, the challenge of their architecture is to efficiently transmit data between network nodes and the node coordinator within given time slots.

As highlighted in [3], the authors discussed recent advancement and progress of mobility-aware MAC protocol in wireless sensor networks categorized into common active/sleep period MAC and slotted TDMA based MAC protocols, preamble sampling MAC protocols and hybrid MAC protocols. The paper proposed models aimed at optimizing the number of sensor nodes by determining their placement to support distributed sensor networks. In their algorithm, their model has not addressed any channel access control mechanisms provided at the MAC layer for prolonging the lifetimes of sensors and error control.

In [4], the authors evaluate a Medium Access Control Scheduling Algorithm (MAC-SA) that enables: an optimal geographic placement of sensors which reduces the required number of sensors to cover a given area to optimize the lifetime of sensor nodes (“SN”). However, the study did not take into account the path loss and temporal variations of the wireless channel in their network connectivity model.

In [5], the authors proposed a good scheduling mobile access scheme by using a CSMA/CA mobile access scheme for the evaluation of an optimized sensor placement for power consumption and packet loss. Nevertheless, slotted TDMA MAC protocol has two main weaknesses: (i) high signalling traffic for setup and maintenance schedules in dynamic topology and (ii) a significant amount of memory that is required for scheduling the nodes.

III. EXPERIMENTAL SETUP

Our placement model is attributed to the complement of a previous study (referred to as RAILMON) [11], which is being done on a single composite node of temperature measurement and object range detection on the TER railway network of Dakar. To address the challenges of our related work, our network architecture is based on a system comprised of two schemes; (i) the optimal placement of the sensors nodes and (ii) an addressing mechanism for channel access method. Hence, each node available on a network can communicate with a suitable MAC Protocol.

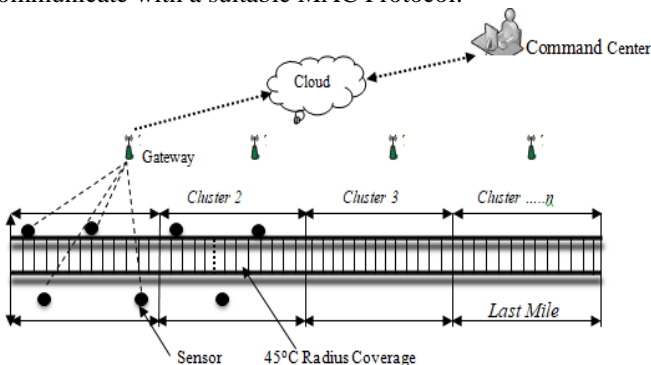


Fig 1: An illustration of triangular sensor placement with transmitting node

The placement approach is divided into two segments, wireless sensor nodes and gateways. Wireless Sensors are the kits responsible for sensing the defined environmental condition and communicates to the gateway at regular intervals through a duty MAC scheduling. The gateway connects to the data repository and the command central responsible for executing necessary remedial action.

The scenario of our sensor placement is modelled for the TER railway network with 14 gate stations along a distance of 67.7 Km range (non LOS) as listed in Table 1 below.

The problem statement is now the determination of the most optimal placement setup of a number of homogenous sensor nodes along the railway perimeter of (M x N) grid, with a design of a the most ideal hybrid MAC protocol that combines the concepts of the common active/sleep period protocols and TDMA in order to get the best duty cycle scheduling for our architecture.

TABLE 1

THE FOURTEEN GATE STATIONS OF THE TER ROUTE

Source Gare	Destination Gare	Distance (Km)
Dakar	Colobanne	4
Coloanne	Hann	4.9
Hann	Baux Maraichers	4.6
Baux Maraichers	Pikine	2.7
Pikine	Thiaroye	2.9
Thiaroye	Yeumbeul	3
Yeumbeul	Keur Massar	6.9
Keur Massar	Mbao	2.5
Mbao	PNR	2
PNR	Rufisque	2.5
Rufisque	Bargny	6.4
Bargny	Diamniado	6.5
Diamniado	AIBD	17.8

In this work, we assume that the nodes are static and the channel variations are dependent on the environment. Our experiment used a static placement of the nodes in a location of the below above table.

A. Measurement Parameters

For the fact that our simulation specifications should best match the features of our transmission radio (LoRa), we proposed to use the Castalia *CC2420* parameter framework with Omnet++ libraries for our simulation [10], which can be tuned to simulate different attributes of our radio parameter e.g. Transmission Power (*TP*), Carrier Frequency (*CF*), Spreading Factor (*SF*), Bandwidth (*BW*) and Coding Rate (*CR*) to evaluate link performance and energy consumption, given the variable conditions.

For the fact that the sensors being modelled are completely homogenous, we considered the use of various geometric placement models ranging from circle, square, rectangle,

octagon, triangle and hexagonal grid placements. We then concluded that after the evaluation of the various geometric models, the coverage range of each sensor can be modelled as a perfect circle grid, which is determined by the radius of the sensor in that modality. We model the effect of the terrain on a sensor's coverage with the radius of coverage that it may be able to provide along different directions.

B. Transmission and Sensing Algorithms

For data acquisition and transmission, each node is programmed to transmit n packets at a given timeslot, so that there are no collisions with other nodes. When a node is transmitting, it constantly listens for incoming packets, and when one packet is received, it increases the counter of the packets heard from the sender node. While this model defines a path loss map, interference is determined as received signal strength and not as a separate feature. All scenarios use the throughput test application, where all nodes send packets to a cluster head at a constant rate.

For this study, we choose LoRaWAN and LoRa motes as our gateway and transmission device respectively. The advent of LoRaWAN encourages single-hop connectivity to gateways as a result of its transmission range based on tunable spreading factors and code rates. In our model, we take into account all the combinations of the possible spreading factors and the three 125 KHz mandatory channels of the 868 MHz band in LoRa transmission.

For an optimized data acquisition mechanism, we analyse the scalability of LoRaWAN for scenarios ranging from single to multiple gateway deployment for an optimal case scenario. In addition, with LoRa mote connectivity is possible even under low SNR conditions because of its robust modulation techniques.

For the sensing attribute, the specifications of the temperature sensor for this study are the DHT11 with radius coverage of 4 meters at 360°C. In that regard, we concluded that while the square lattice provides a fairly good performance for any parameters, hexagonal grid is the worst among all since it has the smallest overlapping area. Triangular lattice is the best among the three kinds of placement as it has the largest overlapping area hence this grid requires the least number of sensors.

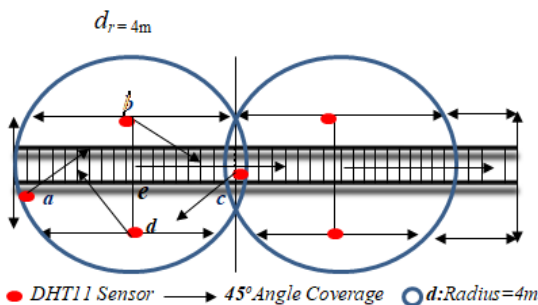


Fig. 2: Triangular lattice placement of sensors in a cluster

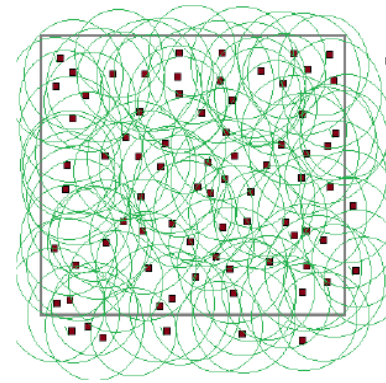


Fig. 3 Illustration of full overlapping coverage of sensors in our model [4]

As highlighted in fig 2 and 3, in most wireless sensor placement as above, it is necessary to ensure full and optimal coverage of the monitored area while deploying the minimum number of sensors. In this regard, while there exists two types of coverage models suitable for optimized static placement; namely simple coverage, and K-Coverage. In our model, we adopted K-coverage (overlapping) which is the extension of simple coverage and suitable for environments such as security surveillance, distributed detection, mobility tracking, military intelligence in battlefields, etc.

For our placement model, we denote that where the Field-Size is denoted as F that needs to be examined by means of a sensor deployment, S is the set of all closed regular geometric shapes such that the shape is fully contained geometrically within a circular area of unit radius. For each point $P \in F$, we define a function $f : F \rightarrow S$ which maps a circular area of unit distance into a geometric shape in S , such that $f(p)$ represents the coverage area of a sensor placed at point P in F . The sensor coverage problem can now be expressed as a circular zone of unit radius, and a field F characterized by the distortion function f . We therefore determine the minimum number of sensors required to obtain coverage of the entire field F .

C. RAILWAY Buckling Measurement

Railway lines have different rate of expansions due to temperature changes when measured to the neutral temperature in railway engineering. While we adopt the use of a standard rail gauge distance of 1435 mm between two side tracks as a realistic environment of our case study on the TER rail network, there are four different types temperature measurement methods in railway engineering; i.e., Strain Gauge method, Ultrasonic method, X-Ray method, Vibration method and Magnetic method.

In our study, we adopt the use of strain gauge temperature measurement technique because of its proven and lasting electromagnetic and ultrasonic experimental capability in hostile rail environments. Where the temperature threshold is set to 60°C for an immediate reaction, we use the temperature force theory of hook's Law, which states that "a law stating that the strain in a solid material is proportional to the applied stress within the elastic limit of that solid".

$$\varepsilon = \frac{\Delta l}{l}$$

Where: ε = Strain in the object [m/m]

Δl = Change in length of the rail track [m]

l = Total length of the rail track [m]

The relation between neutral temperature and sensor detection is: $\varepsilon = \alpha * \Delta T$

Where: α = Coefficient of thermal expansion of the material [m/m/°]

ΔT = Change in temperature for sensor detection [°]

The change in temperature is the difference between the current temperature of the railway and the temperature at the start of heating. The temperature at the start of heating is usually referred to as the neutral temperature, which is the temperature that corresponds to the average stress situation in the rail. When a change in temperature is detected in either rail contraction or temperature threshold within the monitored range, then the sensors become active and broadcast the new values in the network. If a node receives this value from any other node it tries to broadcast it and then sets a flag that it has done its duty, through MAC scheduling.

Alongside the transmission of the temperature variation of the censored location, the gateway will further aggregate the modulation, bandwidth, carrier frequency, and most importantly, the strength of the signal in dBm and send the data to the cloud for analysis and informed decision making.

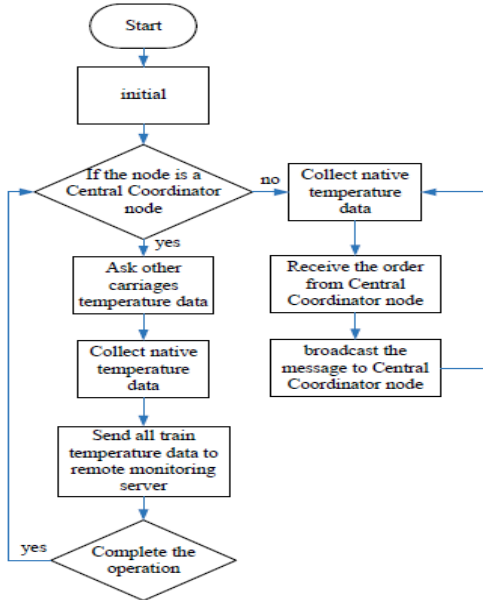


Fig.4 Temperature data capture and process flow chat

IV. EVALUATION OF MAC PROTOCOLS

For the fact that the main purpose of MAC protocols in WSN is to stimulate effective and efficient communication while preserving maximum throughput, minimum latency, communication reliability and maximum energy efficiency, it is paramount to note that in our use case, our measurement technique focuses on two mechanisms, i.e. sensing range and transmission distance. While the sensing node measures a distance of 4 meters range at a radius of 360°C for temperature monitoring, the LoRa transmission range covers a distance of up to 10 kilometres on LoS.

In WSN, when data is transmitted from transmitting node to gateway, [7] the MAC protocol must be carefully designed to avoid extra overhead on the transmission node to the gateway. Hence, there are three common methodologies of designing MAC protocols, precisely referred to as *Common Active/Sleep MAC Protocols (CSMA)*, *Slotted TDMA MAC Protocols*, and *Hybrid MAC Protocols*. The latter being a combination matrix of the Common Active/Sleep MAC with Slotted TDMA-Base MAC Protocols.

To evaluate the performance impact of the protocol mechanism for our work, we performed a number of experiments that test a typical protocol type of each of the four protocol approaches in our network with adaptation and contention, and without adaptation and contention as mentioned below.

A. CSMA MAC Protocol: B-MAC

With the preamble sampling technique, we evaluate and compare the use of Berkeley MAC protocol, commonly known as B-MAC protocol. The protocol is a contention-based protocol, through Low Power Listening (LPL) ensuring power management. With B-MAC, [8] a node maintains a listening duty cycle divided by a specific time period called check interval. Nodes have awake and sleep periods with an independent schedule. For a node to transmit, it precedes data packet with a preamble slightly longer than the receiver's sleep period. A sender is assured with an extended preamble so that the receiver will wake, detect the preamble, and remain awake to receive data. The technique provides wireless access to random multiple nodes without relying on central coordination for the prime purpose of improving the performance of static nodes.

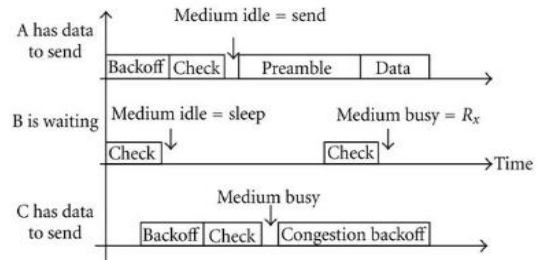


Fig. 5 B-MAC protocol framework

B. Slotted TDMA MAC Protocol: L-MAC

A principal example of the TDMA protocol used in the comparison of our protocol evaluation is the Light Weight

Medium Access Control (L-MAC). L-MAC, a receiver-initiated MAC protocol designed to enable sensors to coordinate their wakeup time with their relay nodes without requiring synchronization or exchanging schedule information, for a sensor node to transmit data packets. This is achieved through a wakeup time self-learning algorithm of a sensor node instead of operating with a fixed wakeup interval period with its parent. This provides further energy-efficiency through a reduction in overhearing and idle listening. The collision-free schedule allows retransmissions, but requires further control among the sensor nodes. It is evident that TDMA-based MAC protocols are thus ideally suited for periodic traffic.

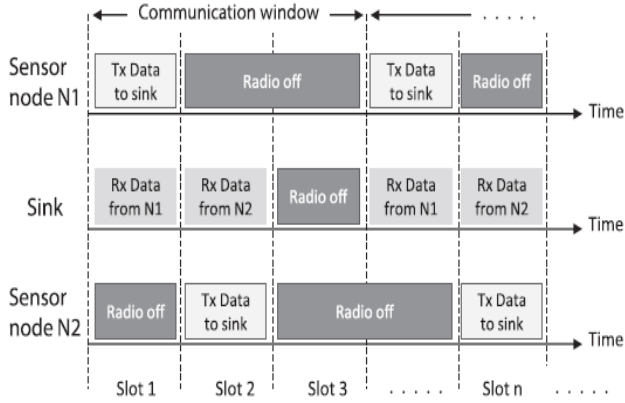


Fig. 6 TDMA protocol framework

C. Hybrid MAC Protocol: H-MAC

A hybrid MAC protocol combines the concepts of the Common active/sleep period MAC with slotted TDMA-based MAC protocols in order to get the best of each. It is based on the IEEE 802.11's power saving mechanism (PSM) and slotted aloha, and utilizes multiple slots dynamically to improve performance.

With H-MAC, channel access is handled through four distinct phases. These are Synchronization, Request/Leave/Join, Schedule Calculation and Distribution, and Data Transfer. The Request/Update/Join (contention-based) phase is used for joining/leaving nodes to request action from the H-MAC. The H-MAC then distributes the schedule, including the TDMA slots, so that the nodes can transmit their data during the transfer phase. Energy-efficiency is improved by sleeping nodes with no data for transmission.

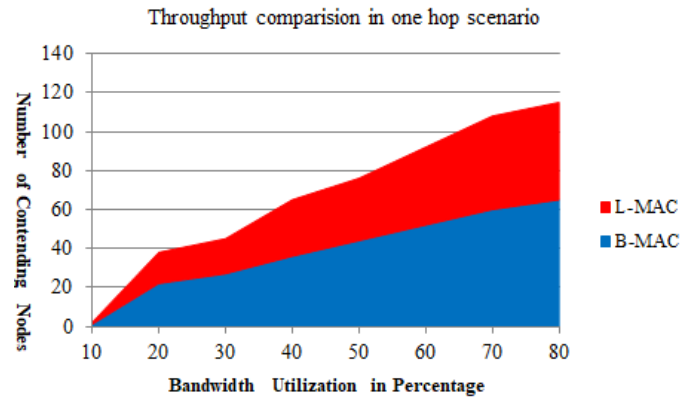


Fig. 7 Throughput comparison of L-MAC and B-MAC protocols for bandwidth utilization

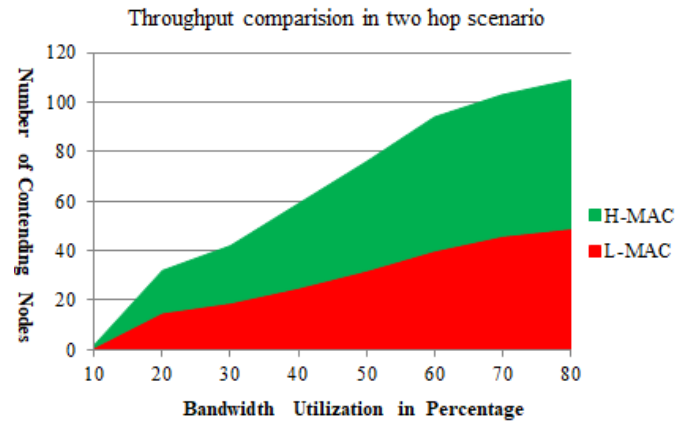


Fig. 8 Throughput comparison of H-MAC and L-MAC protocols for bandwidth utilization

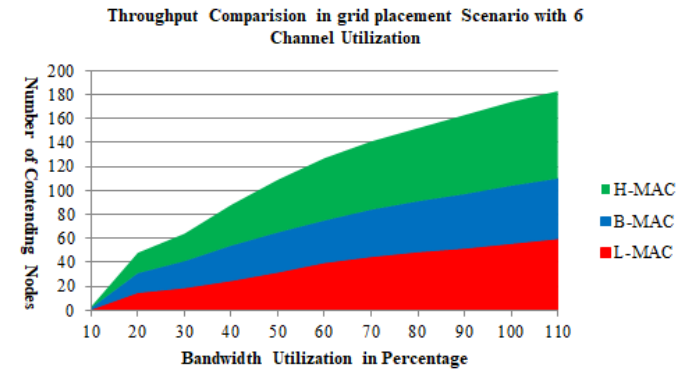


Fig. 9 Throughput comparison of L-MAC and B-MAC protocols for bandwidth utilization

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1:  $M_u \leftarrow$  pre-defined mobility upper bound value
2:  $M_l \leftarrow$  pre-defined mobility lower bound value
3: if number of mobile nodes  $> M_u$  then
4:   Network is mobile
5:   Reduce the frame time
6:   Increase the number of mobile slots as opposed to static
   slots
7: else if Number of mobile nodes  $< M_l$  then
8:   Network is static
9:   Increase the frame time
10:  Increase the number of static slots as opposed to
   mobile slots
11: end if

```

Fig. 10 Algorithm used to determined bandwidth per number of contended nodes for a static placement

V. SIMULATION

To determine the most optimal placement of the number of sensor nodes required per gateway with the use hybrid MAC protocols for our architecture, we created a simulation model for assessing the scalability of LoRAWAN gateway ranging from a single to multiple gateway deployment in order to determine the most optimal deployment of sensors and gateways. We understand the fact that while we can determine the range of LoRa transmission, we assume that for temperature measurement, a grid of sensors can be optimally placed apart from each other up to 300 meters away from each other in order to determine a change in temperature between two distances of a rail track, thus, avoiding a random distribution of sensors. While the physical layer of LoRAWAN operates at 433-, 868- or 915-MHz frequency bands, we considered different settings and change the Spreading Factor (SF), the Preamble Length and the Received Power at the receiver.

We evaluated variants of three protocols of B-MAC, L-MAC and H-MAC Protocols using the OMNeT++ platform in conjunction with CASTALIA libraries to determine the performance of our selected protocols. As highlighted in the figure above, it is evident that the use of slotted TDMA considerably out performed CSMA for the management of collision avoidance the strength of synchronous and asynchronous scheduling mechanism with respect to bandwidth against the number of contending nodes, we explore the function of H-MAC for a better direction for high data rate with low power consumption in both single and multi-hop WSN architectures. Each bit of information is represented by multiple chips of information. By increasing the spreading factor, the number of chips per symbol is increased, thereby decreasing the nominal data rate. Six different spreading factors are used, from 7 to 12, that are orthogonal to each other. This means that if the radio transmitted for 1 second, then it cannot transmit for the next 99 second.

Parameter	Setting 1	Setting 2
Spreading Factor	12	7
Bandwidth	125 kHz	125 kHz
Code Rate	4/8	4/8
Explicit header	On	On
Channel	868.3 MHz	868.3 MHz
Payload CRC	On	On
Programmable preamble symbol length	8	14
Low Data Rate optimization	On	Off
Payload size	17 bytes	17 bytes
Equivalent bit rate	183.11 bps	3417.97 bps
On-air time	1712.13 ms	76.03
Preamble time duration	401.41 ms	18.69 ms
Symbol time	32.77 ms	1.02 ms

Fig. 11 Throughput comparison of L-MAC and B-MAC protocols for bandwidth utilization

Parameter Tuning: Where N , represents the of transmitters; n , denotes the number of packets that each transmitter sends; SF , refers to spreading factor vector; $CHAN$, denotes the channel vector; $Time$, means the Starting time matrix; $RSSI$, the vector of RSSI values for each Tx; $PrHeTime$, preamble and header time; $PrTime$, preamble without last 6 symbols time; t , the time on air of the packet. Each bit of information is represented by multiple chips of information. By increasing the spreading factor, the number of chips per symbol is increased, thereby decreasing the nominal data rate. Six different spreading factors are used, from 7 to 12 that are orthogonal to each other.

```

1 for  $i = 1, i < N, i++$  do
2   for  $j = 1, j < n, j++$  do
3     for  $k = 1, k < N, k++$  do
4       for  $l = 1, l < n, l++$  do
5         if  $(kt = i)$  and  $(SF[i] == SF[k])$  and  $(Chan[i] == Chan[k])$  then
6           if  $((Time[k][l] < Time[i][j] + PrHeTime_i < Time[k][l] + \tau_k)$  or  $(Time[k][l] + \tau_k >$ 
            $Time[i][j] + PrTime_i > Time[k][l])$  and  $RSSI[k] > RSSI[i]$  then
7             Packet  $i$  is lost due to collision.
8           else if  $(Time[i][j] + \tau_i > Time[k][l] > Time[i][j] + PrHeTime_i)$  and  $(RSSI[k] > RSSI[i])$ 
           then
9             Packet  $i$  is received with wrong CRC.
10          else
11            Packet  $i$  is received correctly.
12          end
13        end
14      end
15    end
16  end
17 end

```

Fig. 12 Algorithm to determine the packet collisions and packets received with the wrong

For a further breakdown, we create the packet transmission with the below algorithm; start time matrix $Time [i][j]$, with $i = 1, \dots, N$ and $0 \leq j < n$, N the number of sensor nodes served

by a gateway and n the number of packets that each sensor node has to transmit. To observe the 1% duty cycle of the MAC layer, two consecutive packet transmission start times are separated at least by a time difference of $(\tau \times 100 - \tau)$, with τ the on-air time of the previous transmission. τ depends on the SF used, the *Preamble Symbol Length*, *Header Type* and the *Payload Length*.

$$tn = \sum_{j=1}^n 100 \times \tau_j - 1 + \sum_{j=0}^n \delta_j$$

For a more optimal measurement and evaluation of our simulation model, we ensure that all nodes are static with the same tuning parameter at any given test with the same number of packets to be transmitted.

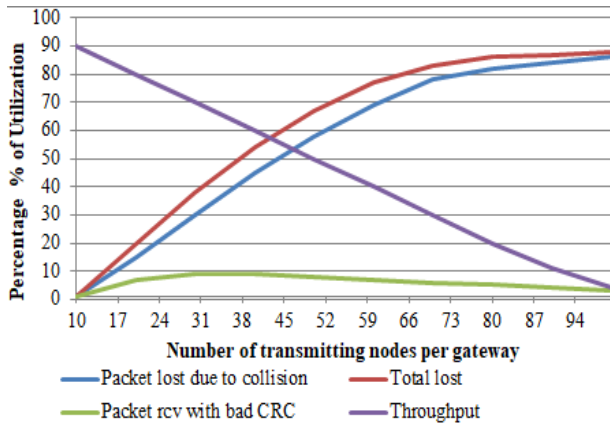


Fig.13 Use of spreading factor 7 with different variations

Percentage of packets lost due to collisions and percentage of packets received with the wrong payload CRC per number of transmitters per gateway. Average throughput per device. Single channel, single SF and payload size 20 bytes using SF 7.

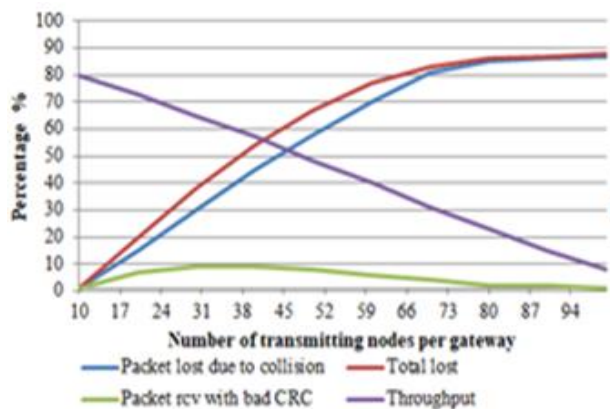


Fig.14 Use of spreading factor 12 with different variations

Figure 13 above highlights the percentage of packets received against the packets lost due to collision as compared

to the throughput capacity of average throughput capacity of the contending nodes to the gateway, which performs only the function of receivership. While graphs of figure 13 demonstrates the effects of SF 7 parameter, the graph of figure 14 below shows the effects of SF 12 with the use of a single channel and payload size of 20 bytes.

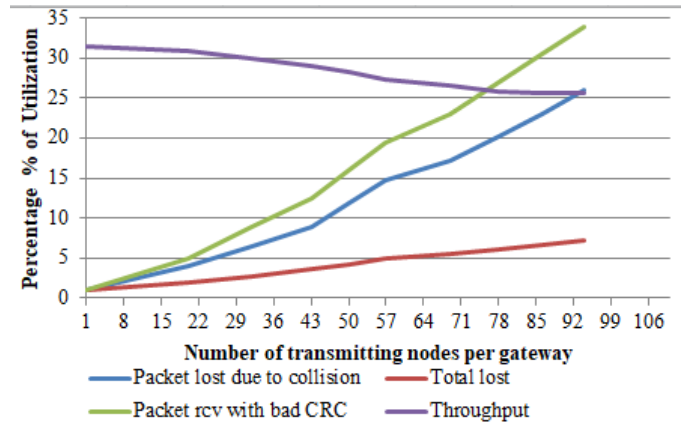


Fig.15 Use of spreading factor 12 with different variations between a comparison of LoRa and pure Aloha with payload size of 20 bytes.

In the same scenario but with a different tuning parameter, figure 15 shows the use of multiple channels with multiple spreading factors. The comparison illustrates the use of LoRa against pure Aloha in terms of percentage of packets lost and average throughput per device.

VI. CONCLUSIONS

In this study, we experimentally prove that, since LoRa uses a robust modulation scheme, by using multiple SFs (7 to 12), the number of logical channels in use can be increased to six with only one physical channel. This is divergent to traditional Aloha-like network modelling, where it is assumed that once part of the packet collides with another packet, both packets will be lost.

The use of H-MAC is therefore more scalable, robust and optimized in terms of the number of nodes contending to a gateway against packet loss and throughput. We further demonstrated the potential of the simulation model to assess the scalability in terms of number of sensors per gateway for heterogeneous sensor nodes with specific application and transmission needs. In the future, we planned to deploy a more integrated wireless sensor node for both temperature and object detection on a single node with multiple functions.

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