Performance Evaluation of Wi-Fi HaLow, NB-IoT and LoRa for Smart City Applications

Richard Verhoeven
p.h.f.m.verhoeven@tue.nl
Eindhoven University of Technology
Eindhoven, The Netherlands

Stash Kempinski
s.p.kempinski@tue.nl
Eindhoven University of Technology
Eindhoven, The Netherlands

Nirvana Meratnia
n.meratnia@tue.nl
Eindhoven University of Technology
Eindhoven, The Netherlands

ABSTRACT

Long-range wireless technologies are at the core of Internet of Things (IoT) and smart city applications. While they offer many advantages in terms of ease of deployment, flexibility, mobility, and ubiquity, to name but a few, they are not equally suitable for smart city applications. Since 'one size fits all' does not hold in this context, finding out which long-range wireless technology is the best requires a thorough performance evaluation of these technologies in specific context and scenarios. In this paper, we focus on performance evaluation of three prominent long-range wireless communications, namely LoRa and Wi-Fi HaLow in the ISM band and NB-IoT in the licensed band, to better understand their benefits and limitations in the context of four smart city application scenarios. These scenarios cover both under and above ground applications in areas with different propagation properties.

CCS CONCEPTS

• **Networks → Network simulations**; *Wireless local area networks*; *Link-layer protocols*.

KEYWORDS

Internet of Things, Wi-Fi HaLow, LoRa, NB-IoT, smart city

ACM Reference Format:
Richard Verhoeven, Stash Kempinski, and Nirvana Meratnia. 2022. Performance Evaluation of Wi-Fi HaLow, NB-IoT and LoRa for Smart City Applications. In *Proceedings of the 19th ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks (PE-WASUN '22), October 24–28, 2022, Montreal, QC, Canada.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3551663.3558596

1 INTRODUCTION

In recent years, the number of Internet of Things (IoT) devices, technologies, standards, and applications has rapidly increased. Smart city is considered as one of the the most popular, yet diverse, application areas of IoT with clear societal impacts. As the cities and their population grow and the borders between cities and urban areas vanish, the demand on long-range wireless communications to cover larger areas with low deployment costs increases. Based on the frequency band they use, long-range wireless communication technologies fall either under licensed mobile frequencies or the unlicensed ISM bands [18]. Each of these two categories has its own benefits and limitations. The licensed mobile frequencies can only be used by authorized/subscribed devices, which limits their wide use and applications and are not for free. However, the use of these frequencies offers the advantage of having higher and managed quality of services. On the other hand, the ISM band is free for use and can be used by any device/user at the cost of having unpredictable quality of service. Co-existence of these licensed and unlicensed frequency bands is yet another challenge for quality of service guarantees in long-range wireless communication [23].

WiFi HaLow, LoRa, and NB-IoT, in the ISM and the licensed mobile frequencies bands, respectively, are considered as long-range wireless technologies suitable for smart city applications. Some articles have presented either a conceptual comparison of these technologies based on standards specification or based on simulation/experimental results (for recent examples see for example [8], [15], [18], [21], [27], [14], [3]). To better understand the benefits and limitations of these three technologies with respect to each other, we define four application scenarios covering both under and above ground smart city applications in areas with different propagation properties. In this context, contributions of this paper include: (i) performance analysis of LoRa, Wi-Fi HaLow, and NB-IoT for different application scenarios and configurations, and (ii) highlighting current challenges and limitations of simulating these standards in the NS3 network simulator [19].

The rest of this paper is organized as follows. In Section 2, an overview of the three protocols is provided. The smart city application scenarios used to compare the protocols are introduced in Section 3. The simulation environment, including propagation and transmission models as well challenges faced in implementing the standards in NS3 are described in Section 4. The simulation setups, their parameters, and their goals are explained in Section 5. Lastly, the results of these simulations, the conclusions that can be drawn from these results, and ideas for future work are presented in Section 6. Section 7 concludes the paper and highlights future directions of this research.

2 LORA VERSUS WI-FI HALOW VERSUS NB-IOT

In this section, we briefly explain the main features of LoRa, Wi-Fi HaLow, and NB-IoT and the parameters which will have influence on their performance.

2.1 LoRa

LoRa is a proprietary modulation technique from Semtech [22], which creates long range, low power communication links, based on Chirp Spread Spectrum (CSS). It operates in the sub-GHz frequency spectrum of 433MHz, 868MHz, and 915MHz, depending on

PE-WASUN '22, October 24–28, 2022, Montreal, QC, Canada

ACM ISBN 978-1-4503-9483-3/22/10.
https://doi.org/10.1145/3551663.3558596

the geographical region in which it is operational [8]. The open communication protocol and network architecture of LoRa as specified by the LoRa Alliance [16] is called LoRaWAN [2].

LoRaWAN supports a star topology and its architecture includes end-devices, gateways, and a network server. According to the LoRaWAN specification [2], end-devices have a single-hop wireless communication to the gateways and the gateways in turn have an IP communication with the network server. Channel access by the end-devices in LoRaWAN is random. LoRa has a long range (< 20 km) but supports only low data rates (< 25 kbps) [4].

An important restriction in LoRaWAN is the duty cycle, which limits communication between end-devices and the gateway to at most 1% of the channel time [7]. This duty cycle restriction has severe consequences in terms of interference and latency. In Europe, LoRaWAN uses the 868MHz licence-free frequency band, within this band different bandwidths are used. The selection of bandwidth, in combination with the spreading factor (SF), determines the throughput and transmission range. According to [22], the advertised maximum transmission range for LoRaWAN is 15 km and the maximum payload size per packet is (in Europe) 222 bytes.

One of important parameters of LoRa modulation is the spreading factor, i.e., the ratio between symbol rate and chip rate [5]. The six LoRa spreading factors, i.e., SF7–SF12, create a balance between data rate and communication range by adapting receiver's sensibility [5]. The higher the spreading factor, the higher reception sensitivity and the lower the data rate. Orthogonality of these spreading factors help communication on the same frequency be collision-free [5].

The LoRaWAN specification distinguishes between three difference classes of end-devices, namely, class A (default), B, and C. The main differences between these classes are, their energy consumption and a(synchronous) downlink connection with the gateway [3].

2.2 Wi-Fi HaLow

Wi-Fi HaLow is one of IEEE wireless networking protocols, i.e., IEEE 802.11ah [11], in the ISM band. In contrary to normal Wi-Fi (IEEE 802.11 ac) that operates in the 2.4 GHz and 5 GHz bands, Wi-Fi HaLow operates in the license-free sub-GHz frequency band. Unlike LoRa, Wi-Fi HaLow has currently no commercially available transceivers. Compared to LoRa, Wi-Fi Halow has a shorter range (< 1 km) but supports higher data rate (150 kbps–346 Mbps) [4].

Since IEEE 802.11ah supports 1, 2, 4, 8, and 16 MHz channel bandwidths, its PHY layer has two designs, i.e., one for 1MHz channel bandwidth and the other one for 2 MHz or higher [25]. For each channel bandwidth, IEEE 802.11ah has defined modulation and coding schemes (MCSs), number of spatial streams (NSS), and duration of the guard interval (GI), which all together lead to support of different data rates [26].

An important property of Wi-Fi HaLow is the Restricted Access Windows (RAW), which allows the devices (stations) only to transmit their data during specific, pre-negotiated time slots. The medium access control RAW is a combination of TDMA and CSMA/CA and the channel is accessed through Enhanced Distributed Channel Access/Distributed Coordination Function (EDCA/DCF) at specific times [26]. Since devices only need to wake up during their RAWs to communicate, this not only reduces the probability of collisions but also help in reducing the battery consumption.

Wi-Fi HaLow supports a star topology. However, unlike LoRaWAN that allows the end-devices to communicate to any gateway, it only allows communication with a dedicated and known gateway (access point). As such, it has a higher initialization cost but ensures that the data remains within the network, making it more private. When a device wants to communicate with the access point (AP), it can randomly select a time slot in its assigned RAW and access the channel. If more devices try to access the channel simultaneously, they may need to back-off to prevent collision and try to access the channel again later. Upon successful channel access, the device requests uplink communication by sending a message to the access point, which will be responded by an acknowledge message to confirm the connection. The access point in return will send another acknowledgement when the data from the device is received [29].

2.3 NB-IoT

NarrowBand-Internet of Things (NB-IoT) is a standard developed by 3GPP [1]. It is an extension of LTE to provide low bandwidth and sporadic communication on licensed mobile communication networks. NB-IoT provides the concept of power save mode (PSM), where devices can turn of their radio components but remain registered to the LTE network. Under normal conditions, the LTE networks provides coverage to nodes by assigning them to base stations and managing the hand-overs of nodes between base stations. However, for NB-IoT nodes, the usage of PSM prevents the hand-overs and therefore also mobility. Using a bandwidth of 200 kHz, NB-IoT provides a data rate of 17-159 kbps, depending on release version and direction. More details about the physical layer of NB-IoT are available in [13].

According to Wirges et.al. [31], the performance of UDP traffic over NB-IoT is considerably better compared to TCP traffic. The 3-way handshake of TCP works less reliable on NB-IoT, such that packets are lost due to connectivity problems. Since LTE uses licensed radio frequencies, where base stations control access to the channel, the reliability and latency properties of the wireless communication are greatly improved.

3 SCENARIOS

We consider four different IoT and smart city application scenarios that cover both under and above ground communications in areas with different propagation properties. More specifically, we consider both countryside (low interference) and urban (high interference) applications. In what follows, we briefly explain each scenario.

3.1 Farm trespassing

The goal of this scenario is to see how each protocol handles relatively large data sizes. As simulation area, we consider an average US farm size, which is 444 acres and translates to roughly 1.8 km^2 [28]. Over this area twelve surveillance posts are evenly distributed, with the AP being placed at the center where the farm house is located, as shown in Figure 1. To simulate trespassers walking around the farm, each post activates up to three cameras in quick succession (i.e., 1 second apart from each other). Posts closer to the AP will activate 1 minute later to resemble the trespasser moving towards the farm house. Both the cameras and the AP are placed 3 meters high.

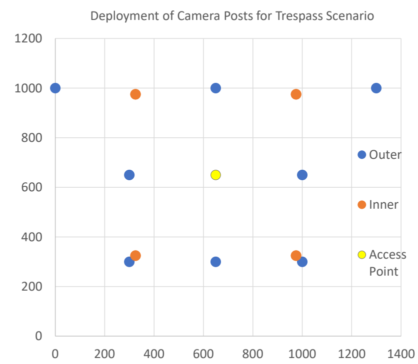

Figure 1: Deployment configuration of 12 camera posts for the farm trespassing scenario. Each post has four cameras and the access point/gateway or the base station is at the center (the yellow circle). In case of LoraWAN, the center location contains 2 gateways, in case of IEEE 802.11ah, it contains an access point, in case of NB-IoT, it contains an LTE base station.

3.2 Waste bins monitoring

A way to optimize garbage collection in a city is through the use of smart bins. For this scenario, smart bins will send a message to the garbage collector when they have to be emptied. The smart bins resent this message every day at midnight until emptied. In the worst case scenario, all nodes will send a message at the same time. Since messages are sent once a day, to make sure that all waste bins are emptied, all messages have to be correctly received and thus a 100% packet delivery rate is required.

The payload of the messages can be an arbitrary 1 byte payload, as the fact that a bin sends this message indicates that it is full. However, if the bin contains multiple compartments for separating waste, the payload could be larger.

The AP is placed 20 meter above the ground, the waste bin transceivers are placed at 1m above ground. The waste bins are positioned according to a square grid, with a gateway or base station at the center, as shown in Figure 2.

3.3 Soil quality monitoring

Long-range communication is a good technology to monitor soil quality in agriculture, for example through the use of wireless communication-enabled devices being buried in a plastic casing with sensors attached to the outside of these casings.

In this scenario, sensors upload their measured soil quality every hour (for monitoring) or when the quality suddenly changes (for generating an alarm). Sensors operate independently and are not synchronized. A packet delivery rate of 100% is required, as a sudden decrease in soil quality can have consequences for the total harvest. Furthermore, missing packets could be interpreted as

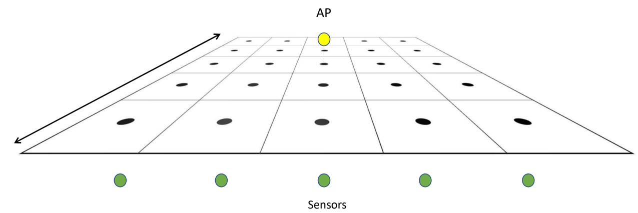

Figure 2: Deployment configuration of the waste bins and soil sensors in a square grid. The access point is placed at the center of the area. Waste bins are positioned 1 meter above the ground, while soil sensors are positioned below ground at a depth that varies per simulation. The example figure presents a 5x5 grid of soil sensors.

broken sensors. The sensor nodes are buried at a certain depth and send a small message of 5 bytes, containing the sensor measurements, to an AP placed 2 meter above the ground. The perspective view of the soil sensor deployment is illustrated in Figure 2.

3.4 Smart sewer system

Chemical substances in sewer systems are currently monitored by taking samples and sending them to laboratories. By placing sensors in the sewer systems, the data collection can be automatized. Additionally, sensors that can monitor quality of the sewer pipes for the purpose of predictive maintenance are gaining popularity. In both cases, these sensors must not be placed too far from each other. The data can be collected in a similar way as the soil quality monitoring scenario. The sensors from the sewer system are positioned according to Figure 3. The AP is placed 2 meter above the ground.

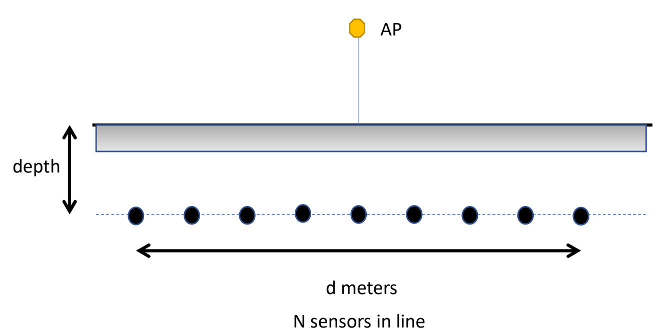

Figure 3: The positioning of sensors in a sewer system

Wireless systems for monitoring a sewer system do exist [6], although they rely on using the maintenance holes to place the radio antennas closer to the surface. For the simulated scenario, we assume that the sensors and antennas are located within the sewer pipe.

4 SIMULATION ENVIRONMENT

4.1 NS3 simulator

For simulations, we used the NS3 simulator [19]. For LoRa simulations, we used the LoRaWAN module created by the SIGNET Lab of the University of Padova [17] in combination with NS3 Version 33. Each simulation used the same gain and sensitivity for all nodes, i.e., 14 dBm and -130 dBm, respectively. The module currently only supports class A devices, meaning that nodes can only send data to a server. They do not receive data (except for confirmation messages).

For the Wi-Fi HaLow simulations, we used the extension created by Tian et al. [26] in combination with NS3 Version 23. All simulations used nodes with 14 dBm transmission gain and -100 dBm sensitivity. Due to module limitations, it was not possible to get the antenna properties to match the settings of LoRaWAN implementation. MCS 3 and spatial stream 1 was used to have as stable as possible connection while achieving a high throughput.

For the NB-IoT simulations, we used the LTE model extension created by Sultania et al. ([24], [12]) in combination with NS3 Version 29. For this wireless communication on a licensed frequency band, the standard gain and sensitivity of the LTE simulation were used.

An overview of our NS3 configuration for different wireless technologies is shown in Figure 4.

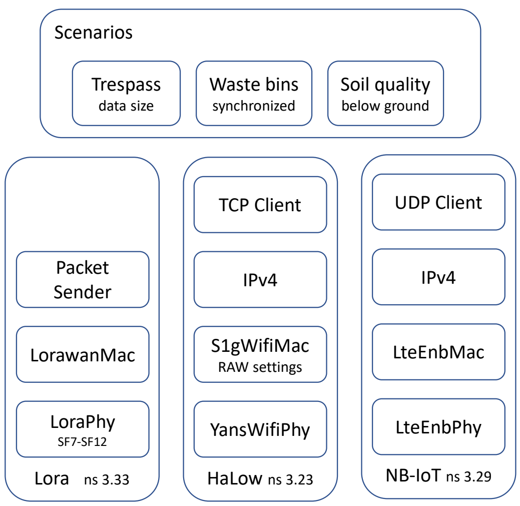

Figure 4: The NS3 configuration for LoRaWAN, Wi-Fi HaLow and NB-IoT

For each technology, the simulated stack consists of a physical layer, a MAC layer, optionally a network layer and an application layer. Environmental conditions, such as propagation loss, are handled by the physical layer were specific models can be connected to the radio channel simulation. The MAC layer simulates access to the radio channel, such as channel sensing and collisions. The network layer simulates the infrastructure required to connect the sender and receiver parts of the application. Finally, the application layer simulates the behavior of the different components according to the different scenarios.

4.2 Challenges of using NS3

As one may notice, we used three extensions of NS3 (for each of the technologies) in combination with three different versions of NS3. Although considerable effort was put in trying to get these three extensions to work in a single (latest) version of NS3, for two of the three extensions, it was difficult to extract those extensions from the NS3 version where they were implemented. The LoRaWAN module is available as a separate module, which can be easily added to a new release of NS3. However, the Wi-Fi HaLow and NB-IoT modules consist of extensive modifications to the Wi-Fi and LTE modules, respectively. Furthermore, those modifications were added to development versions of the NS3 simulator, such that determining which code modifications are specific for Wi-Fi HaLow or NB-IoT is very time consuming. Therefore, we implemented the applications and propagation loss models used for simulating different scenarios in different NS3 versions.

For the NB-IoT simulations, an extension to the LTE module of NS3 was used [24]. The LTE simulation includes a detailed error model for the impact of the radio link quality and selected modulation scheme on the packet error rate. Since performing LTE simulations with NS3 was very time consuming, performance profiling of the simulator was used to determine that most of the execution time is spent on the evaluation of this error model. It should be noted that running the NS3 simulator in production mode instead of debug mode results in a 10-fold performance increase, as the compiler is able to improve the LTE error model evaluation considerably. Furthermore, even when there is no activity in the simulated scenario (that is, neither communication nor movement), the LTE simulation would still perform detailed simulations of LTE behavior for the base stations and nodes to update the radio link quality state. Since NB-IoT does not support the mobility of nodes and puts the radio in power save mode, the performance of NB-IoT simulations with NS3 might be considerably improved by optimizing the LTE error model evaluation for static nodes. Without such optimizations, performing extensive NB-IoT simulations with NS3 is quite time consuming.

4.3 Propagation loss models

The propagation loss models implemented in NS3 are not completely suitable for our considered scenarios. As such we implemented two propagation models, i.e., Weissberger's model [30] and WUSN-PLM [32]. We first briefly explain these models.

4.3.1 Weissberger's model. The Weissberger's model [30] defines the propagation loss of radio waves through vegetation/foliage. It is usable for foliage up to 400m and for frequencies between 230 MHz and 95 GHz, both of which fit the scenarios and protocols being considered. It is important to note that this model only calculates the loss through the foliage itself, and thus should be used in combination with another suitable propagation loss model to completely calculate the point-to-point propagation loss.

4.3.2 WUSN-PLM. The Wireless Underground Sensor Network Path Loss Model [32] is a model with a couple of options including complete underground to underground communication and underground to above ground communication, which is again split into "top soil" (less than 30cm deep) and "bottom soil" (equal or greater than 30cm deep). The model has its accuracy proven through real life measurements of scenarios similar to the soil quality measurement scenario and unlike Weissberger's model, this model is usable on its own.

We used the bottom soil underground to above ground path loss calculation. This calculation is built up from three smaller calculations, i.e., (i) the loss underground from transceiver to enclosing, (ii) the loss through the ground, and (iii) the above ground loss. To accurately calculate the loss through ground, the dielectric constant and loss factor of the simulated ground are needed.

5 SIMULATION SETUP

5.1 Basic setup

The three wireless technologies and the four scenarios result in orthogonal combinations of parameters for the simulations. For the wireless technologies, the following parameters were used:

- For LoRaWAN, the radio frequency was set to 868 MHz (for Europe) and a single channel was used. The spreading factor was varied between SF7-SF12 to determine its effect on coverage and delay.
- For Wi-Fi HaLow, the radio frequency was set to 868 MHz and 5 different settings for the RAW configuration were evaluated.
- For NB-IoT, the radio frequency was set to the licensed LTE frequency of 900 MHz. To support a larger number of sensors using the NB-IoT extension of the LTE module, the SRS periodicity parameter is increased to ensure that all LTE nodes were able to register with a base station. In all scenarios, the height of the LTE base station is set to 27 meters to better reflect their common deployment. The position of the LTE base stations is the same as the LoRaWAN gateways and Wi-Fi HaLow access points, although that would be unlike in practice. As stated previously, since according to Wirges et.al. [31], the performance of UDP traffic over NB-IoT is considerably better compared to TCP traffic, we only consider the UDP traffic.

For each technology, the activation of the simulated sending application was delayed to ensure that energy saving features (such as sleep mode) have taken affect.

5.2 Evaluation scenarios and simulation parameters

We considered four evaluation scenarios and a set of simulation parameters as described below.

- For the trespass scenario, the impact of five different image qualities was evaluated (resolutions 144p, 240p, 360p, 480p and 720p, with respective sizes 3.76 KB, 10.44 KB, 17.64 KB, 31.36 KB and 94.09 KB).
- For the waste bins scenario, the configuration of the deployment area (as shown in Figure 2) was used as simulation parameters. We varied the area side length from 100 to 1000 meters. The grid dimension was varied from 4x4 to 10x10.
- For the soil quality monitoring scenario, the configuration of the deployment area (as shown in Figure 2) and the *depth* (from Figure 3) were used as simulation parameters. For the area side length and grid dimension, the same values were used as in the waste bins scenario. The *depth* parameter was varied from 0.2 to 0.7 meters (in steps of 0.1 meters).
- For the sewer system scenario, the *depth*, N and d parameters of Figure 3 took various values. *depth* was varied from 0.2 to 0.7 meters, the number of sensors N was varied from 4 to 10, and the sewer section length d was varied from 10 to 100.

One may note that the parameters (like *depth* and area side length) for different scenarios overlap, such that results of simulations can be compared.

5.3 Evaluation metrics

To compare performance of different wireless technologies, we used the following performance metrics: packet delivery time and reliability in terms of number of retries required for a successful packet delivery. The packet delivery time is the time between successful reception of the first packet sent and the last packet received. For all scenarios except Scenario 1, only one packet is sent at a time, which means that packet delivery time would be equal to an end-to-end latency.

We do not consider energy consumption as one of our evaluation matrices since authors of [21] have recently compared power consumption of these protocols in the context of Industrial IoT. In their evaluation, the expected battery lifetime was computed for specific scenarios with a periodic communication (once per 10 minutes). In general, the battery lifetime is influenced by the packet size, the communication period, and the interference between nodes (which in turns results in MAC layer re-transmissions). For smart city scenarios without interference between nodes, the expected battery lifetime can be extrapolated from results reported in [21]. For scenarios with interference between nodes, however, an important factor in the energy consumption is the average number of transmissions per MAC layer packet.

We also performed experiments showing how technology specific parameters, i.e., spreading factor for LoRa and restricted access window of WiFi-HaLow impact these metrics.

6 SIMULATION RESULTS AND DISCUSSION

6.1 Farm trespassing

To create a simulation environment that resembles a farm, Weissberger's model [30] and Friis' Transmission equation [9] were used as path loss models. We assumed that 1% of the path between the AP and camera's is foliage. The simulation measures the impact of the image resolution and congestion on the time it takes to transfer a full image on average. These results can be found in Figure 5. In the simulated scenario, within an interval of 100 seconds, 36 cameras attempt to transmit an image with the selected resolution to the gateway at the center of the farm.

For the Wi-Fi HaLow protocol, a configuration was used with 6 RAW groups, each containing 2 slots. A RAW group contains up to 10 stations, assigned consecutively. Since the cameras are activated in sequence, the activity within each RAW group changes over time. Since the Wi-Fi HaLow protocol supports reliable TCP communication, all image transfers were successful.

For the LoRaWAN protocol, the spreading factors 7 and 8 were used and the acknowledged packets had a size of 200 bytes. Due to the 1% duty cycle, the 36 cameras and two gateways should not cause an overload in the network. The simulation reveals that only 9 (for SF7) and 13 (for SF8) images were transferred successfully.

The image transfers were started according to a certain schedule with 1 second intervals, which might cause interference between packet transmissions, acknowledgments and re-transmissions. To prevent repetitive collisions caused by synchronized behaviour between different stations, the LoRaWAN specification introduces the concept of ACK_TIMEOUT, which randomizes the interval between the missing ACK and the re-transmission of the packet to a duration of 1-3 seconds[1]. However, the randomized interval was specified as a minimal delay, while the 1% duty cycle rules still apply. For very small packets using SF7, the randomization can reduce synchronisation, but for the larger packets, it has no effect. As a result, when two stations are running the same application (timing and packet sizes), the interference pattern can continue until one of the stations finishes its transmissions.

For the NB-IoT protocol, each image was sent as a collection of UDP packets. Each UDP packet was divided into a number of LTE transport blocks. Although LTE does support large LTE transport blocks at the MAC layer, the NB-IoT protocol introduces a limit of 17 bytes (according to the NS3 implementation of NB-IoT). Depending on the link quality, the selected modulation scheme reduces the block size further, down to 7 bytes. As a result, a single UDP packet of 1500 bytes may result in 100–200 LTE transport blocks. Since an NB-IoT station can only send one transport block per 10 ms, it results in a large transfer time. Since NB-IoT operates in a licensed frequency band of LTE, access to the radio channel is controlled by the base station, such that collisions between transport blocks of different stations are avoided. The main reason for variations in the transmission time is the selection of a different modulation scheme, resulting in more transport blocks.

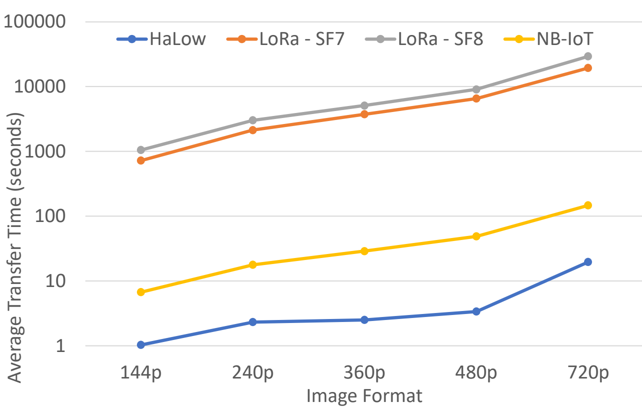

Figure 5: Average transfer times resolution for each protocol

The average number of transmissions for each image resolution can be found in Figure 6 and are used to partly explain the measured transmission times. For Wi-Fi HaLow, the usage of RAW groups and slots reduces the number of collisions, which keeps the number of re-transmissions of a packet low. For LoRaWAN, the 1% duty cycle and the required waiting time results in a noticeable increase of the transmission time when a packet is re-transmitted. In the figure, a distinction is made between successfully transferred images and failed transfers (where a packet was dropped due to the maximum number of retries). For successful transfers, the average number for transmissions per packets is low, similar to Wi-Fi HaLow. For failed transmissions, the consistent interference with other network traffic causes a high number of transmissions per packet, and therefore a larger transmission time (of an incomplete image). Since NB-IoT is using the licensed frequency band of LTE, where the LTE base station schedules the access to the radio channel, re-transmissions due to collisions are avoided. Furthermore, the NB-IoT node adjusts the modulation scheme to improve the delivery ratio, which further reduces the need for re-transmissions of LTE transport blocks.

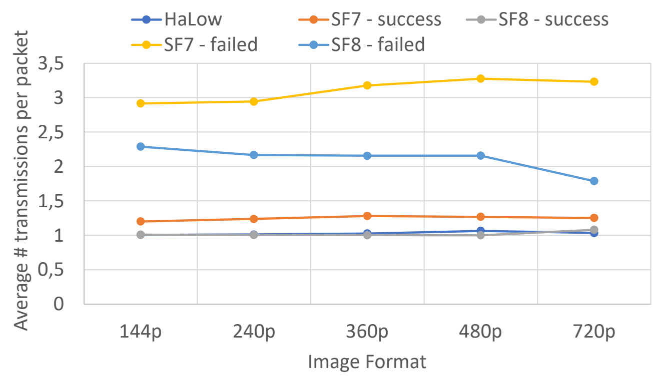

Figure 6: Average number of transmission tries at the MAC layer per packet for different image resolutions for each protocol

6.2 Waste bins monitoring

Since the waste bins are located in the city, this scenario uses the Okumura-Hata propagation loss model [10].

The focus of this scenario is to investigate the effect of synchronized behaviour of all nodes, which means that they all send a message at the same time.

Since the LoRa protocol does not require carrier sensing or a randomized back-off mechanism, all waste bins will start their transmission at the same time, which results in serious interference at the gateway. When the gateway is able to receive a packet, after the gateway has sent the acknowledgment for that packet, the 1% duty cycle rule also applies to the gateway itself, such at the gateway is unable to acknowledge packets that arrive during that interval. As a result, nodes continue to re-transmit, causing severe interference. The LoRa protocol defines a back-off method in case no acknowledgment is received. However, that back-off method only works when the packet size is very small, in combination with a spreading factor of 7, as shown in Figure 7.

The Wi-Fi HaLow protocol divides the nodes in separate RAW groups, such that synchronized access to the radio channel is reduced. In addition, nodes select a random slot within the transmission window for their RAW group and they perform carrier sensing to prevent collisions. For large areas, not all nodes might be associated with the access point due to a poor link quality. However, nodes that are associated with the access point were able to deliver their message.

[1] LoRaWAN Specification 1.1 is not clear about the usage of ACK_TIMEOUT, as mentioned in section 19.1

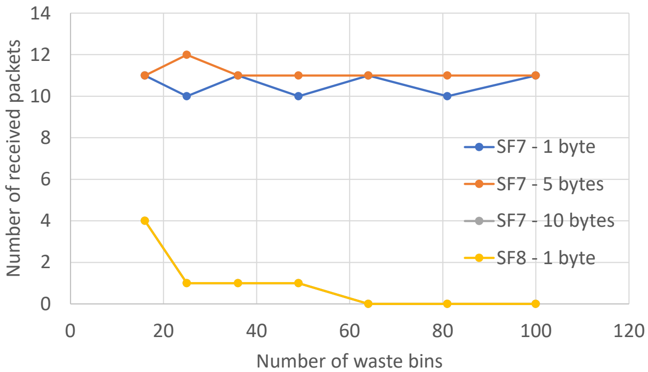

Figure 7: Number for received packets when waste bins transmit at the same time within an area of 200x200 meters. For small packet sizes and spreading factor 7, the back-off method can improve delivery. For larger packet sizes or spreading factor, the method doesn't work.

Using the NB-IoT protocol, all nodes wake up from deep sleep mode at the same time and try to contact the LTE base station to receive a slot for the data transmission. Although this causes some interference between nodes to get channel access, the data transmission of each node is scheduled by the LTE base station which prevents collisions.

In Figure 8, the average, minimum and maximum latency of the packet is presented for different numbers for waste bins within an area of 200x200 meters. For LoRa, due to heavy interference and packet loss, all nodes stop their re-transmissions after the maximum number of attempts (8) is reached. As a result, the maximum latency is independent of the number of nodes. For WiFi-HaLow, a larger number of nodes results in additional interference and packet loss at the MAC layer. However, the use of TCP ensures the content is eventually delivered. For NB-IoT, a larger number of nodes causes some additional delay to change from deep sleep mode to active mode. Once nodes are active, the LTE base station ensures that the packet is received with minimal interference and very low latency.

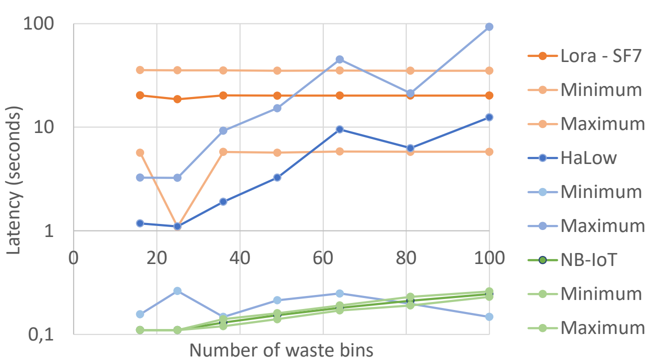

Figure 8: Average, minimum and maximum latency of packet delivery for LoRa, HaLow and NB-IoT

6.3 Soil quality monitoring

The path loss model used for this simulation is WUSN-PLM model [32]. The soil parameters used were the features of clayey silt, as found in [20]. The free space between the transceiver and the casing was set to 3 cm.

The long range of the LoRaWAN protocol, together with the improved sensitivity due to the spreading factors lead to the LoRaWAN protocol to perform well in this scenario. As shown in Figure 9, a larger spreading factor enables a better coverage of the 8x8 grid at a depth 0.3 meters. Figure 10 shows simulation results of all combinations of LoRaWAN parameters.

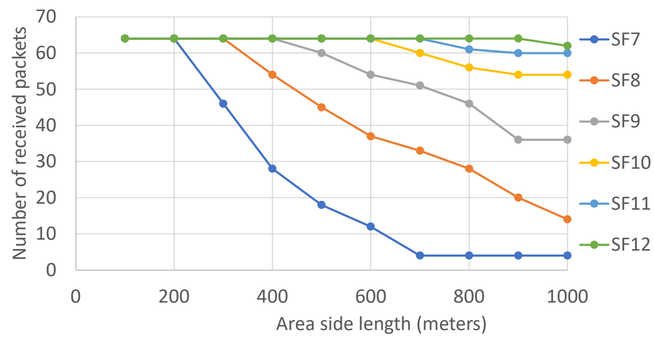

Figure 9: Number of received packets for different spreading factors and area sizes

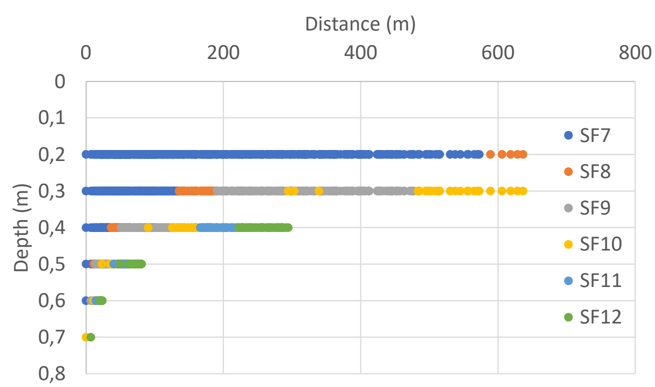

Figure 10: LoRaWAN coverage at different depths for different spreading factors and distances

Simulation results for the Wi-Fi HaLow protocol reveal that the path loss due to the under ground location causes serious coverage issues, where communication is only feasible at a shallow depth of 0.2 meters or directly underneath the access point. As such, the simulations do not reveal interesting results and the RAW groups of Wi-Fi HaLow provide no added value in this scenario, where the time between transmissions of different nodes is large enough to avoid interference.

For the NB-IoT protocol, the default transmission gain and sensitivity settings of LTE were used. With those settings, the path loss for the under ground nodes is such that the selected depths are unreachable.

6.4 Smart sewer system

The smart sewer system scenario has the synchronized behaviour of the waste bin monitoring scenario and the underground behaviour of the soil quality monitoring scenario. Those results are shown in previous figures. The depth of a standard sewer pipe is around 0.6 meters and as such results of this depth in Figure 10 and Figure 8 illustrate that only LoRaWAN may be a suitable solution, under the assumption that gateways are located nearby. The solution, where a communication module is located close to the surface in a maintenance hole, is more viable and easier to maintain.

7 CONCLUSION AND FUTURE DIRECTION

As already explained in Section 2, and now proven by simulation results, LoRaWAN is much more suitable for long distances or difficult conditions (under ground), Wi-Fi HaLow has a much higher throughput, and NB-IoT is more predictable. This means that even though they are all "long range, IoT protocols", they each use different methods to achieve this long range and use vastly different methods that make them suitable for IoT. These methods are focused on saving as much battery power as possible, each with their own set of consequences.

To improve comparability, future work should make sure that the same transmission gains and sensitivities are used between protocols, so the simulation results are independent of the (simulated) hardware that is used.

Updating all modules to the newest release version of NS3 is also a useful exercise to improve comparability and ease of performing simulations.

ACKNOWLEDGMENTS

This research was partially performed within the context of the Dutch 4TU.NIRICT Intelligent Long-range WiFi project.

REFERENCES

[1] 3GPP 2022. The 3rd Generation Partnership Project (3GPP). https://www.3gpp.org.

[2] LoRa Alliance. 2020. *LoRaWAN 1.1 Specification.* Retrieved July 7, 2022 from https://lora-alliance.org/resource_hub/lorawan-specification-v1-1/

[3] Massimo Ballerini, Tommaso Polonelli, Davide Brunelli, Michele Magno, and Luca Benini. 2020. NB-IoT Versus LoRaWAN: An Experimental Evaluation for Industrial Applications. *IEEE Transactions on Industrial Informatics* 16, 12 (2020), 7802–7811.

[4] V. Banos-Gonzalez, M.S. Afaqui, E. Lopez-Aguilera, and E. Garcia-Villegas. 2016. IEEE 802.11ah: A Technology to Face the IoT Challenge. *Academic Press* 16, 11 (2016), 1960.

[5] Pham Congduc, Bounceur Ahcène, Clavier Laurent, Noreen Umber, and Ehsan Muhammad. 2020. Radio channel access challenges in LoRa low-power wide-area networks. *Academic Press* (2020), 65–102.

[6] 2M Engineering. 2022. *IoT sewerage water sensor and monitoring system.* Retrieved July 7, 2022 from https://www.2mel.nl/projects/watersense-wastewater-wireless-monitoring-system/

[7] ETSI. 2004. *Tr 102-313 V1.1.1.* Retrieved July 7, 2022 from https://www.etsi.org/deliver/etsi_tr/102300_102399/102313/01.01.01_60/tr_102313v010101p.pdf

[8] B. Foubert and N. Mitton. 2019. Long-Range Wireless Radio Technologies: A Survey. *Future Internet* 12, 1 (2019), 13.

[9] H.T. Friis. 1946. A Note on a Simple Transmission Formula. *Proceedings of the IRE* 34, 5 (1946), 254–256. https://doi.org/10.1109/JRPROC.1946.234568

[10] M. Hata. 1980. Empirical formula for propagation loss in land mobile radio services. *IEEE Transactions on Vehicular Technology* 29, 3 (Aug 1980), 317–325. https://doi.org/10.1109/T-VT.1980.23859

[11] 2017. IEEE Standard for Information technology–Telecommunications and information exchange between systems - Local and metropolitan area networks–Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation. *IEEE Std 802.11ah-2016 (Amendment to IEEE Std 802.11-2016, as amended by IEEE Std 802.11ai-2016)* (2017), 1–594. https://doi.org/10.1109/IEEESTD.2017.7920364

[12] imec IDLab. 2019. *NB-IoT - Simulator module for NS3.* Retrieved July 7, 2022 from https://github.com/imec-idlab/NB-IoT

[13] Matthieu Kanj, Vincent Savaux, and Mathieu Le Guen. 2020. A Tutorial on NB-IoT Physical Layer Design. *IEEE Communications Surveys and Tutorials* 22, 4 (Fourthquarter 2020), 2408–2446. https://doi.org/10.1109/COMST.2020.3022751

[14] Tian Le, Santi Serena, Seferagić Amina, Lan Julong, and Famaey Jeroen. 2021. Wi-Fi HaLow for the Internet of Things: An up-to-date survey on IEEE 802.11ah research. *Journal of Network and Computer Applications* 182, 103036 (2021).

[15] Antonella Lombardo, Stefano Parrino, Giacomo Peruzzi, and Alessandro Pozzebon. 2022. LoRaWAN Versus NB-IoT: Transmission Performance Analysis Within Critical Environments. *IEEE Internet of Things Journal* 9, 2 (2022). https://doi.org/10.1109/JIOT.2021.3079567

[16] LoRaAlliance 2022. *LoRa Alliance.* Retrieved July 7, 2022 from https://lora-alliance.org/

[17] Davide Magrin, Martina Capuzzo, and Andrea Zanella. 2020. A Thorough Study of LoRaWAN Performance Under Different Parameter Settings. *IEEE Internet of Things Journal* 7, 1 (2020), 116–127. https://doi.org/10.1109/JIOT.2019.2946487

[18] Kais Mekki, Eddy Bajic, Frederic Chaxel, and Fernand Meyer. 2019. A comparative study of LPWAN technologies for large-scale IoT deployment. *CT Express journal* 5, 1 (2019), 1–7.

[19] ns3 2022. *NS3 network simulator.* Retrieved July 7, 2022 from https://www.nsnam.org

[20] Damien Wohwe Sambo, Anna Förster, Blaise Omer Yenke, and Idrissa Sarr. 2019. A New Approach for Path Loss Prediction in Wireless Underground Sensor Networks. In *2019 IEEE 44th LCN Symposium on Emerging Topics in Networking (LCN Symposium).* 50–57. https://doi.org/10.1109/LCNSymposium47956.2019.9000669

[21] Seferagic, Amina and Famaey, Jeroen and De Poorter, Eli and Hoebeke, Jeroen. 2020. Survey on wireless technology trade-offs for the industrial internet of things. *SENSORS* 20, 2, Article 488 (2020), 22 pages. http://dx.doi.org/10.3390/s20020488

[22] Semtech. 2022. *What is LoRa?* Retrieved July 7, 2022 from https://www.semtech.com/lora/what-is-lora

[23] Syed Waqas Haider Shah, Adnan Noor Mian, and Jon Crowcroft. 2020. Statistical Qos Guarantees for Licensed-Unlicensed Spectrum Interoperable D2D Communication. *IEEE Access* 8 (2020), 27277–27290.

[24] Ashish Kumar Sultania, Carmen Delgado, and Jeroen Famaey. 2019. Implementation of NB-IoT Power Saving Schemes in Ns-3. In *Proceedings of the 2019 Workshop on Next-Generation Wireless with Ns-3* (Florence, Italy) *(WNGW 2019).* Association for Computing Machinery, New York, NY, USA, 5–8. https://doi.org/10.1145/3337941.3337944

[25] W. Sun, M. Choi, and S. Choi. 2013. IEEE 802.11ah: A Long Range 802.11 WLAN at Sub 1 GHz. *Journal Of ICT Standardization* 1, 1 (2013), 83–108.

[26] Le Tian, Amina Šljivo, Serena Santi, Eli De Poorter, Jeroen Hoebeke, and Jeroen Famaey. 2018. Extension of the IEEE 802.11ah Ns-3 Simulation Module. In *Proceedings of the 10th Workshop on Ns-3* (Surathkal, India) *(WNS3 '18).* Association for Computing Machinery, New York, NY, USA, 53–60. https://doi.org/10.1145/3199902.3199906

[27] Stephen Ugwuanyi, Greig Paul, and James Irvine. 2021. Survey of IoT for Developing Countries: Performance Analysis of LoRaWAN and Cellular NB-IoT Networks. *Electronics* 10, 18 (2021). https://doi.org/10.3390/electronics10182224

[28] National Agricultural Statistics Service USDA. 2020. *Farms and land in farms 2019 summary.* Retrieved July 7, 2022 from https://www.nass.usda.gov/Publications/Todays_Reports/reports/fnlo0220.pdf

[29] Yanru Wang, Kok Keong Chai, Yue Chen, John Schormans, and Jonathan Loo. 2017. Energy-aware Restricted Access Window control with retransmission scheme for IEEE 802.11ah (Wi-Fi HaLow) based networks. In *2017 13th Annual Conference on Wireless On-demand Network Systems and Services (WONS).* 69–76.

[30] M. A. Weissberger. 1982. An initial critical summary of models for predicting the attenuation of radio waves by trees. Final Report Electromagnetic Compatibility Analysis Center.

[31] Joschka Wirges and Uwe Dettmar. 2019. Performance of TCP and UDP over Narrowband Internet of Things (NB-IoT). In *2019 IEEE International Conference on Internet of Things and Intelligence System (IoTaIS).* 5–11. https://doi.org/10.1109/IoTaIS47347.2019.8980378

[32] Damien Wohwe Sambo, Anna Forster, Blaise Omer Yenke, Idrissa Sarr, Bamba Gueye, and Paul Dayang. 2020. Wireless Underground Sensor Networks Path Loss Model for Precision Agriculture (WUSN-PLM). *IEEE Sensors Journal* 20, 10 (2020), 5298–5313. https://doi.org/10.1109/JSEN.2020.2968351