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Research of LoRaWAN productivity performance models for building IoT networks

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ABSTRACT

The study of the LoRaWAN method application performance models in the IoT networks, which is currently being intensively developed, improved and is an important component of the information society. LoRa is a new long-range, low-power wireless technology that is key to building IoT networks around the world. Unlike other wireless technologies, the signal range and autonomy are enormous. Unlike GSM networks, it does not require bulky equipment with a high level of radiation. It can be easily used in places with mass construction without harm to human health. Two main scenarios for modeling performance improvement were investigated. Based on the results of the research, it is concluded that doubling the bandwidth effectively doubles the baud rate, and increasing the bandwidth reduces the sensitivity of the receiver, while increasing the propagation factor increases the sensitivity of the receiver. It is shown that by slightly changing the ACK procedure, it is possible to significantly improve the system performance in terms of packet delivery factor, system capacity, and energy efficiency. Conversely, it is determined that other system parameters are already well configured.

Keywords: LoRaWAN; IoT; modeling; post-mortem; Lora; command and control systems

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INTRODUCTION

With the development of technology, the concept of IoT is gaining more and more space in various fields: home appliances, gadgets, manufacturing (IoT), medicine, transport, logistics, security, climate control and many others. In addition to computers, multimedia systems and smart TVs, the “smart home” will use many devices with a local short-range connection, including devices to control temperature, lighting, locks and alarm systems. The benefits of smart home technologies will be implemented in the areas of heating and protection of commercial buildings, sewerage, street lighting, energy conservation and traffic optimization through adaptive control of maximum speed limits and traffic lights [1]. Communication is one of the most important parts of any IoT project. Although there are many communication protocols, each of them lacks certain characteristics, which makes them “not quite suitable” for IoT applications. The main problems empirical measurements, mathematical analysis and simulation tools. Some LoRaWAN works, such as are energy consumption, coverage radius and bandwidth. Most communication radio technologies, such as Zigbee, BLE, WiFi and others, have a short range, while others, such as 3G and LTE, consume a lot of energy and their range cannot be guaranteed, especially in developing countries. Although these protocols and communication modes work for certain projects, they have major limitations, such as difficulties in deploying IoT solutions in non-cellular areas (GPRS, EDGE, 3G, LTE / 4G) and the need to purchase expensive licenses.

Thus, given the future of IoT and the connection of all kinds of “things” located in all places, there is a need for a communication environment specifically designed for IoT, which supports its requirements, in particular, low power and long range, cheap, secure and easy to deploy.

LITERATURE REVIEW

In recent years, LoRaWAN technology is state-of-the-art. The subject of many studies, which analyzed its effectiveness and features of

[2, 3] test coverage range testing and packet loss rate using empirical measurement, but without investigating the effect of parameter adjustments on performance. Other works, such as [4], study the effect of modulation parameters on the connection between the end device and its gateway, without taking into account more complex network configurations.

To obtain more general results [5], a stochastic geometry model is used for joint analysis of time interventions and frequency domains. It is noticed that with the implementation of the packet repetition strategy, i.e., the transmission of each message repeatedly, the probability of failure decreases, but the average bandwidth decreases due to the introduced redundancy.

In [6], the author proposes closed forms for packet collision and loss probabilities, which show the assumption of perfect orthogonality between SFs, show that the distributed Poisson process does not accurately model packet collisions in LoRaWAN.

Network bandwidth, latency, and uplink collision rates are analyzed in [7], using queuing theory and considering the Aloha channel access protocol and regulatory restrictions on the use of different subbands, indicating the importance of intelligently splitting traffic in available subbands to improve network performance. In the [6] mathematical model of network performance, factors such as the capture effect and realistic distribution of SFs in the network are taken into account. However, the model does not include some important network parameters, preventing the study of their impact on network efficiency.

A step further is made in [8], where the authors develop: a model that allows taking into account various configuration parameters, such as the number of ACKs sent by GW, SF, used for downlink transmissions, and DC restrictions imposed by regulations. However, multiple retransmissions were not considered in this paper.

The study presented in [9] contains an analysis of the LoRaWAN system layer and provides significant information about bottlenecks and network behavior in the presence of downlink traffic. However, in addition to pointing out some design flaws in the LoRaWAN middle access scheme, this work is not appropriate in order to suggest any way to improve the performance of the technology.

System-level simulations are again used in [10] to evaluate the effectiveness of confirmed and unconfirmed messages and show the detrimental effect of traffic confirmation on overall network bandwidth. The only proposed solution is to use multiple gateways, without in-depth study of the LoRaWAN standard.

In [11], a module for the ns-3 simulator is proposed and used for a similar field, comparing scenarios of single and multilateral movement and the use of unconfirmed and confirmed messages. In this case, the authors correctly implement several GW reception paths, but do not take into account their association to a specific UL frequency, which usually occurs during network setup: indeed, the number of packets that can be received simultaneously at a given frequency should not exceed the number of reception paths. is on this frequency. Also in this case, the study focuses on the analysis of effectiveness, without proposing any improvement.

The authors in [12, 13] focus on the original ADR algorithm proposed [14], which suggests possible improvements. As a rule, modified algorithms give network increase, scalability, uniformity between nodes, packet delivery factor and resistance to changing channel conditions.

In [14], the authors calculated the optimal distribution of SFs to minimize the probability of collision and proposed a scheme to increase uniformity for nodes remote from the station by optimally assigning SF and transmit power values to network nodes to reduce packet error.

In [15], shows how the use of a stable MAC Multiple Access Protocol (p-CSMA) carrier in UL messaging can improve packet reception. However, it should be noted that having many EDs that delay transmission due to low p values can lead to underutilization of the channel.

In [16], the authors use simulations to investigate the effect of DC limitation in LPWAN applications, where they show the possibilities of course adaptation that are essential to maintain a reasonable level of performance when the coverage range and cell load increase. However, the effect of adjusting other parameters on network performance is not taken into account.

GOALS AND OBJECTIVES OF THE RESEARCH

In this study, in differ from the existing literature, we focus on large networks with two-way traffic, the use of which allows us to observe some unintended effects arising from the interaction of several service nodes in a single GW and NS.

In addition, in the analysis we study:

1) The role played by customizable network parameters, thus highlighting some pitfalls that may affect network performance.

2) Possible countermeasures that require small changes at the MAC level, and we evaluate their effectiveness in some applications.

CONFIGURED MODELING PARAMETERS AND SCENARIOS

The LoRaWAN standard [17] defines the MAC and the network of control protocols for devices that use LoRa modulation.

Network topology is a star [19, 20] formed by three types of devices:

Terminal device (ED): a peripheral node, usually a sensor or drive that communicates only through LoRa PHY;

Gateway (GW): An intermediate node that transmits messages between ED and NS. ED and GW communicate using LoRa modulation, while communication between GW and NS is carried out using outdated IP technology. Usually gateways are equipped with LoRa chipsets; allow parallel reception of several signals.

Network Server (NS)

A centralized entity that manages network settings, forwards messages to programs, and sends responses to the end device through a gateway (the UL packet is a request to the NS, and the corresponding DL packet is the response).

Network settings available

Familiarity with the network configuration parameters available in the simulator and which are designed to control the behavior and features of both GW and EDs [18]:

– Gateway: the simulator has the ability to enable or disable the DC limit on the GW to analyze its impact on network performance.

– Transmit / Receive Priority: Because GW cannot receive and transmit at the same time, this parameter determines the relative transmission priority (TX) over reception (RX) in the event of a conflict. If priority is given to RX, then the transmission of DL packets will be delayed until the reception is completed (provided that the corresponding reception window is opened). Conversely, if priority is given to TX, the reception of any input signal will be immediately interrupted to start DL transmission. Note that to date, the transfer of priority is the only option available in commercial GWs.

– Priority under the range: the required LoRaWAN standard, RX1 opens on the same channel where the corresponding UL was received, and RX2 opens on a dedicated DL channel, which also has in Europe softer DC restrictions (10 % instead of 1 % allowed on other channels). The simulator has a mode that toggles this setting, making it possible to open RX1 on the dedicated DL channel and RX2 on the channel used for UL communication.

– Confirmation of data rate: LoRaWAN specifications recommend using ACKs transmitted on RX1 of the same SF for UL transmission, when transmitting on RX2 use the lowest available data rate (SF = 12). The simulation module has been modified to allow the use of higher data rates for both reception windows. [21, 22] This parameter provides a compromise between reliability and efficient use of available DC and time resources.

This option can actually be implemented in LoRaWAN using specialized MAC command.

– Number of transmission attempts: for confirmed traffic, the maximum number of transmission attempts m for the configured message can be set to {1, 2, 4, 6, 8}.

– Full duplex GW: as already mentioned, currently GW cannot transmit and receive simultaneously. However, it may be interesting to investigate the potential effectiveness of the gain obtained from the implementation of full duplex GW. This functionality can be implemented by placing two GWs or combining a GW with a simple LoRa chipset, which should only be used for transmissions, leaving the GW free to receive messages. To test this functionality, we added: a new mode for the lorawan module in the ns-3 simulator that allows perfectly full-fledged duplex communication.

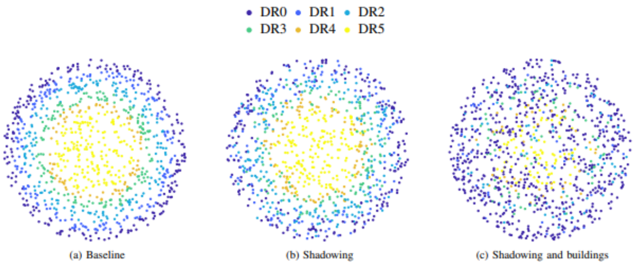
– Number of reception paths: the number r of parallel reception paths in GW is a parameter that can be changed in the simulator. In addition to the standard value of r = 8, we also considered the values of r = 3 and r = 16 to study how parallel GW reception capabilities can affect overall system performance.

Two main simulation scenarios were investigated.

Since the main goal is to optimize the parameters of the MAC layer, it is assumed that one GW, which serves several EDs that generate packets periodically, with equal periods, but random phases. In addition, device-generated traffic can be acknowledged, unacknowledged, or mixed, that is, with half of the devices requiring acknowledgment and the other half sending unconfirmed packets.

The first scenario assumes that the EDs are randomly distributed within the GW coverage, and we only consider path loss.

The second scenario consists of a more realistic urban deployment, where EDs are randomly located outside or inside a building with different wall heights and widths, the next model. Here, the spread of the canal affects the loss of path, spatially correlated shading and weakening due to the presence of buildings. To get a realistic setting, you need to consider the model traffic described in Mobile Autonomous Reporting (MAR), according to which devices send packets in periods ranging from 30 minutes to 24 hours. The number of devices also varies for power estimation



(a) Baseline (b) Shadowing (c) Shadowing and buildings

Fig. 1. **Distribution of data tariffs for different channel models**

***Source*: compiled by the authors**

Performance indicators

Packet transmission at the PHY level can have five possible outcomes:

1. Success (S): The package was received correctly by GW.
2. Lost due to sensitivity (U): The packet arrives at GW with less than power and GW cannot block it.
3. Lost due to interference (I): the packet is properly blocked by GW, but it cannot be retrieved due to a sufficient number of packets, with sufficient power to disrupt orthogonal signals.
4. Lost through saturated receiver (R): the packet arrives at GW with sufficient power, but all parallel path reception tuned to the packet transmission channel is already busy receiving other packets.
5. Lost due to GW (T) transmission: packet reception is disrupted when transmitting a DL packet (which may be long at the time of packet arrival, starts during packet reception if GW gives priority to transmission).

In the case of unconfirmed traffic, we mark the packet as successful when it is successfully received on GW, which, in turn, forwards it to the NS via a secure connection. For confirmed traffic, we distinguish two cases depending on whether the DL packets carry information (for example, a UL packet is a request to NS, and the corresponding DL packet is a response), or just an ACK used to stop retransmission of UL packets. In the first case, the transmission is successful when both the UL and the serial DL packet are successfully received by the NS and ED, respectively, within the available transmission attempts.

In the latter case, instead, it is assumed that the transmission is successful if at least one of the generated UL packets is delivered to the NS, regardless of whether the ACK is received by the device.

Accordingly, two performance indicators are determined:

1. Confirmed packet success rate (CPSR): the probability is confirmed by a UL packet, and the corresponding DL packet is correctly received in one of the available transmission attempts;
2. Uplink Packet Delivery Ratio (UL-PDR): The probability of a UL packet being received correctly (regardless of whether an ACK is requested).

IDENTIFICATION OF NARROW LOCATIONS AND SYSTEM DYNAMICS

Basic efficiency analysis

To begin with, it is necessary to compare the achieved results of confirmed / unconfirmed traffic in mixed and homogeneous scenarios, for the proposed traffic at the application level. Solid lines in Fig. 2, show UL-PDR for confirmed and unconfirmed cases only (crossed and circle markers, respectively), while dotted lines refer to the efficiency of the two types of source traffic experiences in the mixed scenario. It can be seen that the mixture of confirmed and unconfirmed traffic sources contributes to the first class of sources.

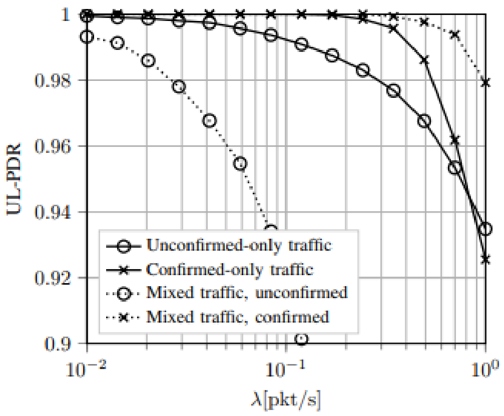


Fig. 2. **Basic UL-PDR performance for different types of traffic**

***Source*: compiled by the authors**

Focusing on homogeneous traffic scenarios, it is seen that the use of confirmed traffic maximizes the UL-PDR index to a total traffic load of almost λ = 0.7 pkt / s at the program level (excluding retransmissions). At this point, it is more convenient to use only unconfirmed communications. The reason for this behavior is shown in Fig. 3, which reports the share of packet losses caused by different events for two homogeneous scenarios analyzed earlier. The results were obtained for the proposed traffic λ = 0.7 pkt / s, for which UL-PDR is the same for both homogeneous scenarios. Having only unconfirmed packet traffic losses is mainly due to interference (I) created by multiple UL transmissions. On the other hand, confirmed traffic (with m = 8), in addition to interference losses, also suffers from other disturbances, such as saturation of the GW pathway (R) and collisions with ASA (T), which play a major role among the causes of failure. Therefore, validated traffic can expand network data collection capabilities while the overall load is low, but it can significantly degrade the performance of the PHY layer for higher loads, which in turn impairs scalability.

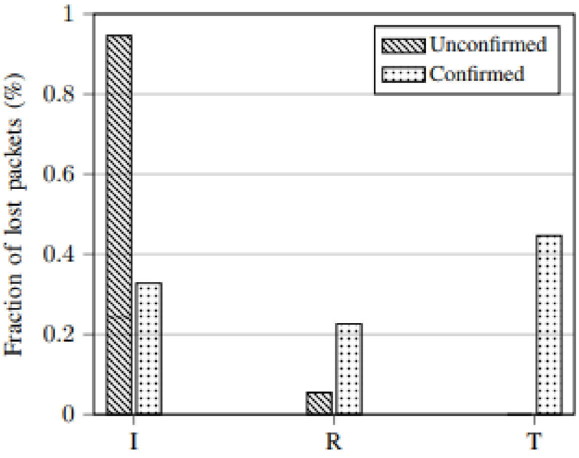


Fig. 3. **PHY results for traffic that provides the same ULPDR**
***Source*: compiled by the authors**

DC gateway

The effect of DC limitation on GW is only visible when confirmed traffic requires EDs. The solid line with cross markers in Fig. 4 shows the CPSR performance baseline obtained in the case of only confirmed traffic. A solid line with markers gives instead a CPSR, which can be obtained by removing the DC limit on GW. Comparing the two curves, it can be seen that the DC limitation on GW represents a serious bottleneck for the CPSR condition since the successful receipt of UL packets was not recognized by the NS in due time due to the GW DC limitation. In addition, missed ASCs increase the transport load of the UL, causing the re-transmission of otherwise successfully delivered UL packets.

Priority of transfer before reception

The effects of intake priority (RX) on GW should have been studied in terms of both CPSR (Fig. 4) and UL-PDR (Fig. 5). It is worth noting that the RX priority can be implemented on the GW, simply by avoiding DL packet transmissions if at least one of the eight circuits is received in parallel.

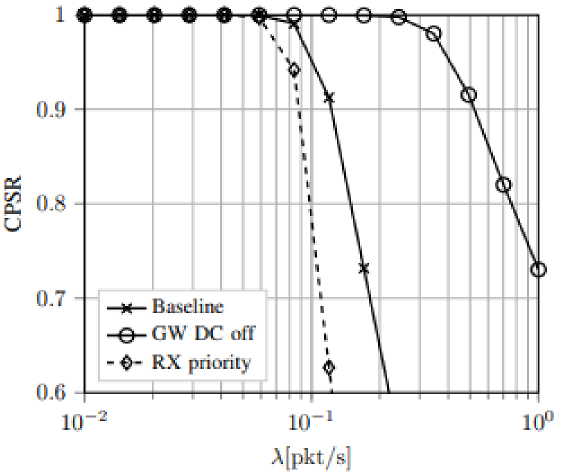


Fig. 4. **CPSR networks with only verified traffic sources**
***Source*: compiled by the authors**

Fig. 4 shows that giving priority to RX leads to loss of CPSR. In fact, as λ increases, the number of UL packets successfully received by GW increases faster than the default when TX is priority, and the probability that GW is in reception is rapidly approaching 1, thus preventing GW from transmitting ACK. This, in turn, triggers the retransmission of packets from the devices. On the other hand, as shown in Fig. 5, in mixed traffic scenarios, RX priority improves the efficiency of both confirmed and unconfirmed traffic sources in terms of UL-PDR. In summary, prioritizing RX over GW allows you to receive more UL packets, but this can lead to DL channel congestion.

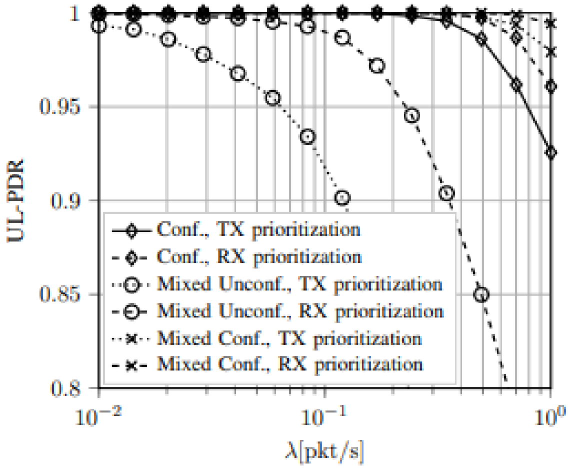


Fig. 5. **UL-PDR performance for unconfirmed, validated, and mixed traffic when RX or TX is a priority**
***Source*: compiled by the authors**

More generally, DL packets may be denoted by NS based on their importance to the ED, explicitly signaled by the MAC header bit, or NS is inferred based on the program that generates the flow data).

If ACKs are required, the DL packet can be marked as a priority before receipt and sent to the GW immediately. If, on the other hand, the acknowledgment is simply used to stop relay and the ED is only interested in maximizing its UL-PDR, then ACKs may be marked as low priority and GW will only send them in standby mode.

ACK options

The impact of two options on standard validation mechanisms called ACK bandwidth substitutions and data rates, which seek to alleviate bottlenecks by limiting DC power to GW and improving system performance through bandwidth and energy efficiency, is analyzed.

1. Subband Replacement: As mentioned earlier, the RX1 always opens in the same subband as used for UL transmission, while the RX2 opens in the subband reserved for DL transmission with a DC current of 10 %. Therefore, ASA sent RX1 will compete with other UL transmissions, generating and interfering, and can quickly consume 1 % DC of this below range. Therefore, we investigated whether there could be any benefit from substituting the bands used for RX1 and RX2: therefore, we applied a substitution scheme under the range according to which RX1 opens in the reserved DL range, while RX2 opens in the common below the range used for UL transmission.

2. ACK Data Rate: LoRaWAN's highest available SF (and therefore lowest DR) in RX2 is used by default to increase the likelihood that a downlink packet will be received correctly. However, this can be detrimental, as longer ACK transmission times quickly consume GW DC. To study which effect is dominant, an “ACK data rate scheme” is implemented, where all DL transmissions are always performed on the same DR as for the corresponding UL transmission.

In Fig. 6, CPSR is achieved using the default setting (solid line with a cross marker), each of the ASK improvement schemes (dotted lines with square and diamond markers, respectively), and both improvements together (dotted line without a marker).

We can observe that the substitution under the band has a very small (but positive) effect in terms of CPSR, which means that the interference produced by UL transmissions to DL reception is not very important. Conversely, the use of the same DR in all reception windows brings significant profits in terms of CPSR at the baseline.

From this we can conclude that the use of the lowest DR in RX2 can severely limit system performance, in particular, skipping reception in RX1 is not due to channel disruption, but by limiting the DC GW in this range.

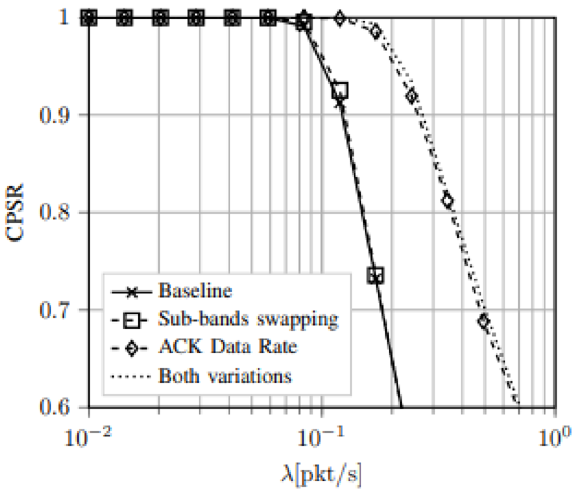


Fig. 6. **Impact of improvements on CPSR**
***Source*: compiled by the authors**

The best strategy to ensure efficient and reliable DL transmissions is to implement independent speed adaptation strategies on all sub-DL ranges.

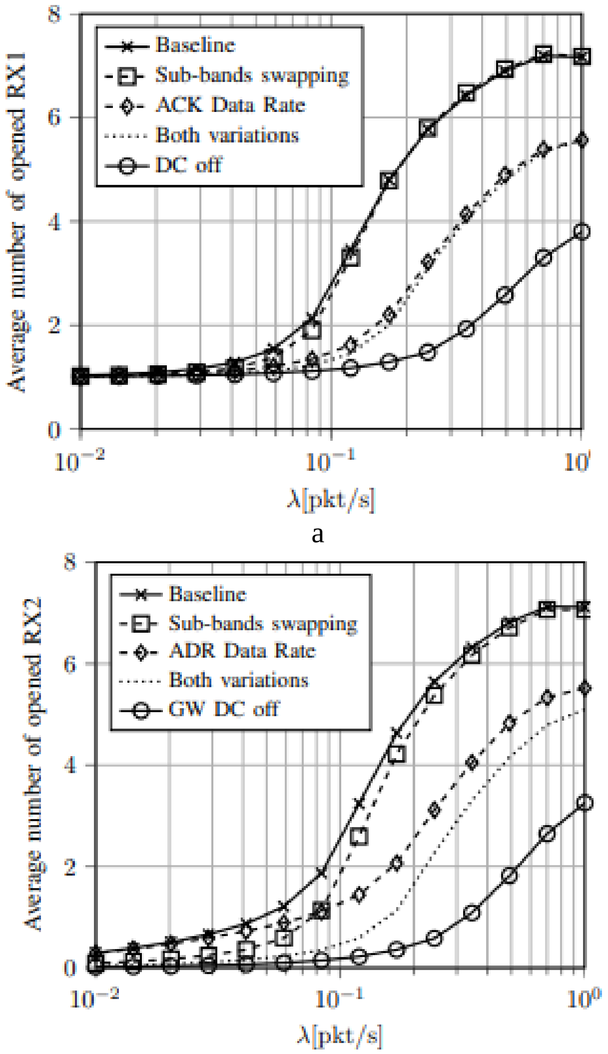
Two ASA improvement schemes also have a positive impact on energy consumption. Indeed, the subband replacement mechanism makes it possible to return more ACK to the RX1, thanks to the lost DC limitation of the DL-reserved subband, thus avoiding the need to open the RX2. This effect can be observed in Fig. 7, which shows the average number of times RX1 (above) and RX2 (below) EDs, with the maximum number of relays set to $m = 8$. However, the gain tends to disappear as traffic increases, because then both subbands will be used to return ACK.

We can also notice this by using the same DR in both reception windows, which significantly reduces the average number of open reception windows for transmission, as well as for relatively high traffic.

Indeed, by transmitting DL packets at a higher speed, this helps to facilitate DC excitation, allowing GW to service more devices. In turn, this reduces the number of retransmissions and the number of RX1 and RX2 that need to be opened.

This is easily explained by considering the DL traffic type, the network (where ACK queues are always full) will be generated when the proposed enhancements are on and off: in the standard case, long DL transmissions using low data rates will be accompanied by long DC waits.

During these periods, GW will be forced to listen to the network, which will improve ULPDR performance. If, on the other hand, GWs send short DL packets, they can do so more often and in turn play more UL packets through DL transmission.



a

b

Fig. 7. **Impact of the proposed ACK improvements on the average number of open windows RX1 and RX2: a – RX1; b – RX2**

***Source*: compiled by the authors**

This behavior can be counteracted by prioritizing RX over TX: Fig. 8 shows that with this configuration we get the best, while achieving UL-PDR improvements and energy saving benefits obtained by switching under bands and using the ACK data rate scheme.

Number of transfer attempts. The results showed that increasing the maximum number of m transmission attempts improves CPSR by 5-10 % (although the return decreases sharply as m increases).

On the other hand, as we see in Fig. 9, smaller values may slightly improve UL-PDR in mixed traffic scenarios.

In particular, at λ = 1 pkt / s, choosing m = 4 instead of m = 8 does not significantly change the UL-PDR for confirmed traffic, but gives an improvement in UL-PDR of unconfirmed traffic, which confirms the sensitivity of network performance to set this parameter.

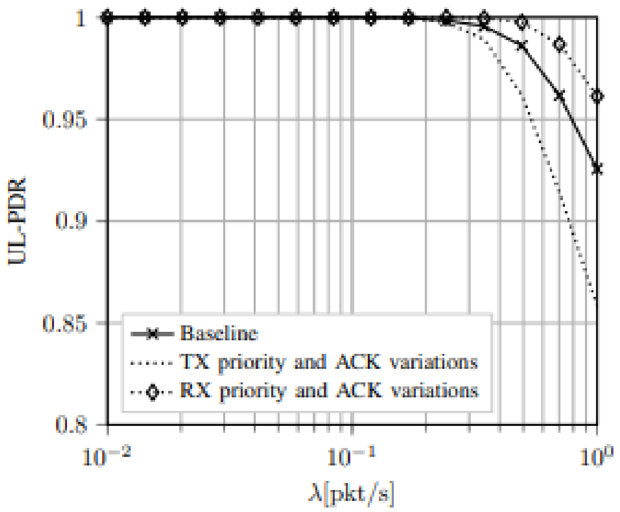


Fig. 8. **UL-PDR performance in the case of only confirmed traffic**

***Source*: compiled by the authors**

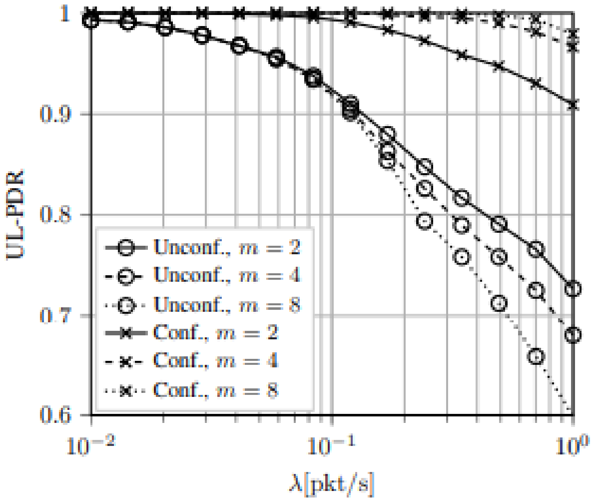


Fig. 9. **UL-PDR for mixed traffic, different values of m**

***Source*: compiled by the authors**

The best configurations in a realistic scenario

The final campaign was aimed at assessing the results of the impact, which offered options for the operation of the sensor network deployed in the real city, including the channel model and SF distribution, the configuration of which is summarized in Table.

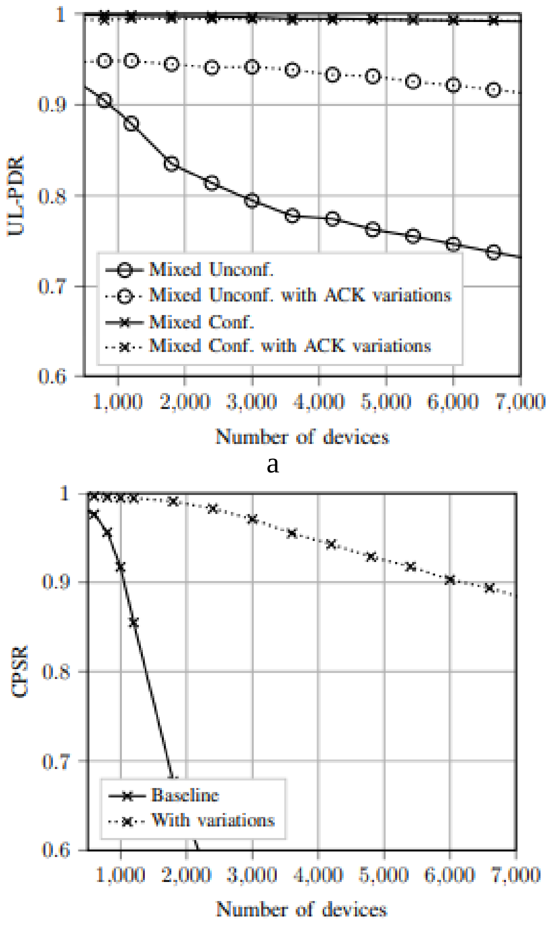
The results were built against the number of devices in the cell to give an idea of the increase in power achieved by intelligently adjusting the operating parameters of the network.

Table. **Times of interaction in realistic modeling**

Time between arriving	% of devices
1 day	40
2 hours	40
1 hour	15
30 minutes	5

***Source*: compiled by the authors**

In Fig. 10a shows how UL-PDR can be improved with the proposed configuration which contains up to 4 times more unconfirmed devices that could be serviced with standard settings.



a

b

Fig. 10. **Simulation results for a alistic scenario:**
a – UL-PDR; b – CPSR

***Source*: compiled by the authors**

Similarly, Fig. 10 shows that the number of devices that can be granted CPSR is greater than 0.95 when the proposed options are used.

CONCLUSIONS

The study concluded that, with a standard configuration of settings, the presence of verified traffic sources can significantly degrade the performance of unconfirmed traffic due to additional interference created by DL transmissions (ACK).

In the confirmed traffic, the most critical factor was the limitation of the DC current GW, which suppresses the DL channel, which soon becomes a bottleneck in the presence of bidirectional flows.

More interestingly, we noticed that by slightly changing the ACK procedure (namely, introducing substitution mechanisms under the range and data rate of ACK) and the priority of reception over transmission to GW, it is possible to significantly improve the system performance in terms of packet delivery factor, system capacity, energy efficiency and justice, in particular in the presence of mixed sources of movement.

Conversely, other system parameters: the maximum number of transmission attempts and the number of parallel paths are already well configured.

So, as we can see, since LoRa networks are used in many areas.

The technology allows simplifying and automate the operation of control, monitoring and control systems:

Resource meters. Street lighting. Leak detectors. Environmental monitoring. Smart parking lots. Agriculture and much more. Advantages of LoRaWAN-network: long-range, energy consumption, permeability, unlicensed range.

Thus, IoT technologies can increase business efficiency by eliminating daily work and saving employee’s time; reduce the number of staff and also the payment of wages; improve products and services based on collected and analyzed data.

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Дослідження моделей продуктивності застосування метода LoRaWAN для побудови мереж IoT

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АНОТАЦІЯ

У роботі проведено дослідження моделей продуктивності застосування методу LoRaWAN в мереж IoT, яка в даний час інтенсивно розвивається, удосконалюється і являється важливою складовою інформаційного суспільства. LoRa – це нова бездротова технологія далекого радіусу дії та малого споживання енергії, яка є переважною для побудови мереж Інтернету речей у всьому світі. На відміну від інших бездротових технологій – колосальна дальність сигналу та автономність. На відміну від мереж GSM не вимагає громіздкого обладнання з високим рівнем випромінювання і може бути легко використаний у місцях з масовою забудовою без шкоди для здоров'я людей. Було досліджено два основні сценарії моделювання покращення продуктивності параметрів. На основі результатів виконаних досліджень зробилені висновки, що подвоєння пропускної здатності ефективно подвоює швидкість передачі, а збільшення пропускної здатності знижує чутливість приймача, тоді як збільшення коефіцієнта розповсюдження збільшує чутливість приймача, також зниження швидкості коду допомагає знизити швидкість помилок пакету при наявності коротких появ перешкод. Показано, що незначно змінивши процедуру ACK, можливо значно покращити систему продуктивності щодо коефіцієнта доставки пакетів, ємності системи, енергоефективність. І навпаки визначено, що інші системні параметри вже добре налаштовані.

Ключові слова: LoRaWAN; IoT; моделювання; побудова мереж; LoRa; системи управління та контролю

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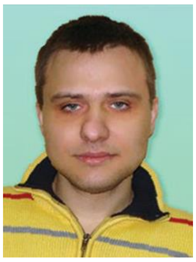

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