Experimental throughput models for LoRa networks with capture effect

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***Abstract*—The Long Range (LoRa) modulation keeps gaining relevance in the landscape of low-power sensor networks. Most models used to evaluate the performances of LoRa deployments are based on the assumption that two colliding frames are necessarily lost. Recent findings have shown that the capture effect occurs in these networks, allowing the receiver to sometimes demodulate the frame featured with the highest signal power. This finding notably improves the overall throughput compared to expectations, but in turn decreases the network fairness. In this paper, we analyze the benefits and drawbacks of such an effect. We therefore provide new throughput models for LoRa networks operating Pure and Slotted ALOHA access schemes. For this purpose, an experimental testbed has been setup and used to measure the occurrence probabilities of capture events in several transmission scenarios. The resulting models are validated with real-life data gathered on the same setup. We additionally analyze the fairness in our deployment, showing that the devices featured with the highest average power at the receiver benefit from a higher success rate than others. By computing Jain's index, we show that this unfairness gets more pronounced as the traffic load increases.**

***Index Terms*—LoRaWAN, LPWAN, MAC Protocols, Capture Effect, Experimental models, IoT**

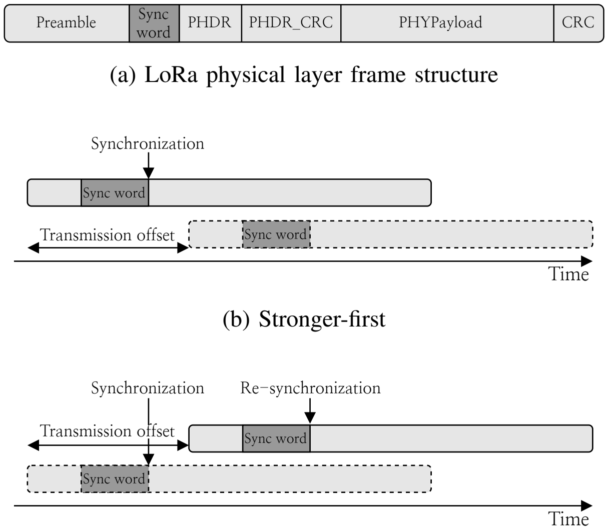
I. Introduction

In the past years, Long Range (LoRa) networks emerged as a means to provide Internet access to low power sensors [1]. Indeed, the proprietary LoRa technology achieves a very high receiver sensitivity at the cost of a low data rate thanks to the Chirp Spread Spectrum (CSS) modulation [2]. This makes it suitable for long-range, low-throughput communications that fit a wide range of Internet of Things (IoT) applications. The open LoRaWAN Specification [3] details the Medium Access Control (MAC) protocol for networks using the LoRa modulation. In details, the basic access scheme is Pure ALOHA [4], meaning that devices are allowed to trigger transmissions without getting synchronized or sensing the radio medium beforehand. This is the simplest access scheme able to save the scarce energy stored in batteries. However, frame collisions become more frequent when the number of competing terminals increases. This means that the maximum achievable throughput is limited and the network's ability to handle high traffic loads is restrained. On this regard, the research community has evaluated synchronization as a means to increase the scaling capabilities of LoRa deployments [5]–[8]. In more details, aligning all devices on a common time reference allows to fit transmissions within predefined timeslots, which reduces the frame collision probability. In that, even a simple Slotted ALOHA access [9] doubles the maximum achievable throughput compared to its unslotted equivalent. The Pure and Slotted ALOHA throughput models most commonly used to evaluate LoRa deployments [10] are based on the hypothesis that two colliding frames are inevitably lost. However, recent findings [11], [12] prove that the capture effect occurs in such deployments. This physical layer phenomenon describes the possibility that when several frames are transmitted simultaneously on a radio medium, the one featured with the highest Received Signal Strength Indication (RSSI) at the receiver may successfully be demodulated. As a result, the aforementioned models widely underestimate the actual throughput observed in LoRa networks.

This paper therefore provides new throughput models that picture the network performances more faithfully by taking the capture effect into account. Due to the unpredictable nature of the radio medium, the occurrence of capture events is subject to randomness. To quantify this random component and take it into account in our modeling, we combine the theoretical approach with testbed measurements. For this purpose, we first of all establish the theoretical occurrence probabilities of several transmission scenarios. Then, each scenario is reproduced for a large number of iterations on an experimental testbed in order to estimate the capture probability in such situation. All scenarios are finally aggregated, and the resulting experimental models prove to be consistent with real throughput measures gathered on the same testbed. In an effort assess present and future MAC protocols for LoRa, the Pure and Slotted ALOHA access schemes are both evaluated.

Besides an overall increase of the maximum achievable throughput, the occurrence of capture events imply that some devices benefit from a greater share of the total throughput than others. Indeed, transmitters featured with the highest average signal power at the receiver will prevail in most capture scenarios. Their frames therefore have more chances to be successfully demodulated than the average. In that, the network fairness is degraded. In an effort to quantify this phenomenon, Jain's fairness index [13] has been computed with our experimental data. Results show that the fairness degrades as the traffic load increases, for both the Pure and Slotted ALOHA schemes.

The rest of this paper is organized as follows. Section II provides background on the capture effect and its impact on LoRa deployments. Our experimental throughput models are introduced in Section III. This modeling is then validated



(a) LoRa physical layer frame structure

(b) Stronger-first

(c) Stronger-last

Fig. 1: LoRa receiver synchronization and capture scenarios

with testbed measures in Section IV. Insights on the impact of such effect on the network fairness and a discussion of our results are given as well. Finally, concluding remarks and future envisaged works are provided in Section V.

II. Background and related works

When several frames collide in a wireless network, not all of them are necessarily lost. Indeed, the RSSI difference and transmission offset between the involved frames may allow one transmission to be successfully demodulated by the receiver. This phenomenon is referred to as *capture effect*, and has been observed in several types of wireless networks. Semtech typically assumes a 6 dB noise figure for the LoRa receiver architecture [14]. As a result, most related works [15]–[17] define a 6 dB RSSI difference between colliding frames as a requirement to benefit from the capture effect. However it was shown in [18] and [19] that capture events could be observed even with threshold values between a 0 and 5 dB. In [20] this threshold is evaluated in greater details, and expressed as a function of the signal-to-noise ratio and spreading factor of the considered transmission. These findings therefore reveal that using a fixed 6 dB value leads to underestimating the actual throughput and coverage probability of LoRa deployments.

During a capture event, the demodulator behavior differs depending on whether the strongest packet arrives first or last at the receiver. We will now precisely describe these scenarios in order to approach related contributions with insightful details. The LoRa physical frame structure (as presented in the LoRaWAN specification [3]) is recalled in Figure 1a. In such a frame, the preamble allows the receiver to detect the presence of a packet, and the synchronization word is used to precisely align the demodulator with the arriving symbols [21]. After that, the physical header PHDR indicates the data size. The PHDR_CRC indicates whether a Cyclic Redundancy Check (CRC) will be used or not. PHYPayload contains the physical payload, and CRC carries the optional CRC value. In the event of a stronger-first capture scenario (*c.f.* Figure 1b), the demodulator synchronizes to the packet featured with the highest RSSI. Then, it may retrieve its content without being affected by other frames if their relative power is sufficiently low to avoid interference. However when the frame featured with the lowest RSSI value arrives first (*c.f.* Figure 1c), the receiver starts its processing and then detects the preamble of the other one. At this point, it may be able to re-synchronize to the second frame and process it normally if its relative RSSI is sufficiently high.

These two scenarios have notably been described in [22], where the authors exploit the capture effect with a collision detection and recovery technique. They show that this method allows to retrieve information in the failing frame header for the stronger-last case. Such data can then be used to identify the terminal that lost a frame and setup a recovery procedure (*e.g.* trigger a retransmission or adapt the device's transmission parameters). In [11], Bor *et al.* experimentally measured the probability of occurrence of capture events in a LoRa network. They notably demonstrated that the capture probability strongly depended on the transmission offset between the two concurring frames in all capture scenarios. This fact must therefore be considered when modeling the asynchronous pure ALOHA access scheme, that leads to frame offset variations. In [12], the CSS technique that characterizes the LoRa modulation has been mathematically modeled while accounting for the capture effect. Results show that a successive interference cancellation technique could also take advantage of the capture effect to decode even the weaker LoRa signal, thus further improving the network performances. This interference mitigation strategy has also been explored in [23], which additionally proposes to combine information from all receiving gateways to achieve a more reliable decoding.

The impact of capture effect on the throughput of wireless networks is a well-known topic, and has been modeled in the context of of Pure [9] and Slotted [24] ALOHA access schemes. Interestingly, several recent contributions have studied the interactions between the capture effect and some characteristics of LoRa networks. In [25], Bankov *et al.* evaluate the Packet Error Rate with numerical results, and validate them with simulations. Contrary to us, they focus on LoRaWANs using acknowledgments and retransmissions. Besides, we validate our models with experimental data instead of simulations. The authors of [26] propose another model that additionally considers the multiple demodulating paths available on typical LoRa gateways. Indeed most gateway concentrators are capable of demodulating up to 8 frames in parallel, which has an impact on the network capacity especially when several orthogonal Spreading Factors (SF) are used. The authors additionally tackle the problem of Spreading Factor allocation, and use simulations to validate their numerical results. Contrary to them, we focus on experiments with the smallest SF because it offers the highest data rate and lowest energy consumption. An experimental evaluation of the capture effect has also been led in [19], in which the capture probability is assessed for a range of RSSI differences between several LoRa frames. Experimental data is then fed into a simulator to evaluate the overall network performances, but no model is derived. To the best of the author's knowledge, the mathematical and experimental approaches have never been jointly applied to LoRa networks in the existing literature. This paper therefore provides new models that accurately describe the LoRa performances thanks to an experimental evaluation of the capture effect. We additionally use Jain's index to quantify the fairness drop induced by capture events.

The modeling methodology used in this paper is in fact inspired of [27]. Indeed, Kosunalp *et al.* evaluated the capture effect in IEEE 802.15.4 networks (for Pure ALOHA only) by experimentally assessing several transmission scenarios and modeling the occurrence probability of each. We apply this idea to Pure and Slotted ALOHA access schemes, and extend it to account for single packet failures as well.

III. Throughput modeling with capture

The most common ALOHA throughput models [10] are derived considering that two or more (even partially) overlapped frame transmissions do not allow the correct decoding of any frame. In a real-world deployment, these hypotheses are not necessarily met. For the case of a single ongoing transmission, unfavorable channel conditions may lead to a failure. This is emphasized by the fact that LoRa operates over unlicensed ISM bands, in which many concurring networks are potentially interfering with each other. On the other hand, when several transmissions overlap, the strongest one in terms of Received Signal Strength Indication (RSSI) may still be demodulated by the gateway according to the capture effect.

In order to determine more accurate Pure and Slotted ALOHA throughput models, we conduct an experimental study inspired from the methodology presented in [27]. We consider the overlapping transmission of 1 up to 3 frames for Pure ALOHA, and up to 5 for Slotted ALOHA. By noting i the number of overlapping transmissions, we define the *occurrence probabilities* P_i (for Pure ALOHA) and P_i^* (for Slotted ALOHA) of such events (*c.f.* Section III-A). These scenarios are then reproduced for a large number of iterations on the real hardware testbed in order to evaluate their respective *success coefficients* C_i and C_i^*, representing the average probability that a packet can successfully be demodulated in each scenario (*c.f.* Section III-B).

The Pure ALOHA throughput T (in Erlangs) is naturally obtained by aggregating the success probabilities of all the three scenarios, weighted by their respective success coefficients:

$$T = \sum_{i=1}^{3} \left(P_i C_i\right) \tag{1}$$

Setting up a Slotted ALOHA scheme requires a means to share a common time reference with all terminals. For this purpose, we leverage the LoRaSync mechanism introduced in [8] because it ensures an energy efficient synchronization while being robust to clock drift issues. With LoRaSync, margins are added to each slot based on the worst-case drift that may occur between two synchronization events. A portion of the time is also reserved for the reception of synchronization beacons. When computing the Slotted ALOHA throughput (in Erlangs), we must therefore consider the fraction of time available for transmissions α :

$$T^* = \alpha \cdot \sum_{i=1}^{5} \left(P_i^* C_i^*\right) \tag{2}$$

A. Transmission scenarios and their occurrence probabilities

For this modeling, we make the hypothesis of a finite number of devices n generating a Poisson traffic with parameter λ. All frames are featured with the same Time on Air (ToA), which is used as the reference time unit. For Pure ALOHA, we introduce the probability p that any device generates a frame during such time unit:

$$p = 1 - e^{-\lambda} \tag{3}$$

To model Pure ALOHA, we consider the scenarios where the transmissions of 1, 2 and 3 frames are overlapped. This access scheme operates smoothly for low traffic loads, where higher-order overlaps are very rare and can be neglected. For the single frame transmission scenario, we introduce the probability P_1 that one and exactly one device transmits a frame during a time unit. It is in fact equal to the classical Pure ALOHA throughput model [10] in which capture effect is not considered.

$$P_1 = np(1-p)^{2(n-1)} \tag{4}$$

The probabilities that 2 and 3 packets overlap during a time unit, respectively P_2 and P_3, have been computed by Kosunalp *et al.* [27], and their expressions are:

$$P_2 = n(n-1)p^2\left(\frac{(1-p)^{2(n-2)}}{2} + (1-p)^{2n-3}\right) \tag{5}$$

$$P_3 = \frac{n(n-1)p^3(1-p)^{2(n-2)}}{2}(2n-3) \tag{6}$$

As mentionned before, LoRaSync uses margins to handle the device clock drift. For this reason, the LoRaSync slot size L_{slot} is bigger is than the frame ToA. We therefore define p^* the probability that any device generates a frame during such a slot:

$$p^* = 1 - e^{-\lambda L_{\text{slot}}} \tag{7}$$

For Slotted ALOHA the transmission scenarios are easier to model and experimentally reproduce because frames always arrive simultaneously on the transmission medium. We therefore consider the cases of 1 to 5 simultaneous transmissions. The probability P_i^* that exactly i frames are generated for the duration of a LoRaSync slot can be expressed with the binomial coefficient:

$$P_i^* = P(i \text{ in } n) = \frac{n!}{i!(n-i)!} p^{*i}(1-p^*)^{n-i} \tag{8}$$

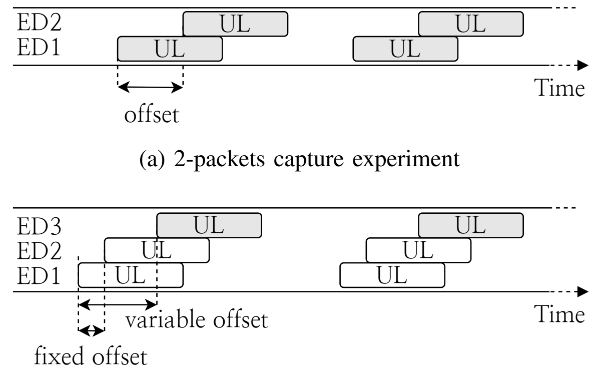
TABLE I: Measured success coefficients

C_1	C_2	C_3	C_1^*	C_2^*	C_3^*	C_4^*	C_5^*
0.88	0.42	0.23	0.88	0.49	0.44	0.25	0.19

B. Experimental setup and capture coefficient measurements

In this part we detail all experiments used to measure the success coefficients C_i and C_i^*, which represent the probability to correctly demodulate a frame in several transmission scenarios. All resulting values are provided in Table I. An experimental LoRa testbed has been setup with LoPy 4 devices, a Raspberry Pi 3 gateway equipped with an IMST IC880A LoRa concentrator and a custom network server. In this contribution we are not studying the impact of very heterogeneous RSSI values on the capture coefficients. Indeed, as mentioned in Section II, it was shown that the capture effect could be observed even with RSSI gaps below 6 dB. We therefore minimize the RSSI variation by placing all devices next to each other, and setting the transmission power to the maximum 14 dBm value on all of them. The following experiments show that capture events can be witnessed even when all devices are setup identically. We need to synchronize all devices on the same time reference to reproduce the following experiments consistently. For this purpose, we use the LoRaSync synchronization mechanism [8]. This way we are able to tightly control transmission offsets while keeping the timing error below 5 ms. Herein, we use an outdoor gateway equipped with a GPS chip in order to trigger synchronization beacons with great precision. To facilitate experiments, devices are placed indoor are therefore not in a direct line of sight with the receiver. It should be noted that even with this setup where all devices are setup identically, we still witness an uneven RSSI distribution as we will see in Section IV-B. These received power differences may be imputed to small differences in the positioning of antennas, multipath fading and uncertainties in each hardware component. In any case, our approach consists in estimating the capture coefficients for our setup through the repetition of capture scenarios, and for that we do not need to know the exact RSSI differences between frames nor what causes them. SF7 is used in conjunction with the typical 125 kHz bandwidth for all experiments throughout this paper, and only the 868.1 MHz channel is used. In an effort to minimize the amount of transmitted overhead, all frames are featured with the maximum ToA allowed for SF7, *i.e.* 389.376 ms.

For the asynchronous transmissions occurring when using a Pure ALOHA access scheme, the capture probability depends on the degree of overlap between the interfering packets [11], [27]. In order to evaluate the 2 packets overlap case, the experiment represented in Figure 2a has been reproduced for 15 evenly spread offset values. At each offset, over 200 repetitions have been realized for statistical relevance. We then compute 15 intermediary capture coefficients by dividing the number of capture events (*i.e.*, a frame coming from one of the two devices has successfully been demodulated) by the number of iterations. C_2 is finally obtained by averaging all intermediary coefficients. For the 3-packets overlap case,



(a) 2-packets capture experiment

(b) 3-packets capture experiment

Fig. 2: Pure ALOHA capture coefficient measurement

the experiment represented in Figure 2b has been realized. This time we vary the offset between the second and third packet, and a fixed 50 ms offset is used between the first two. A similar approximation has been done in [27], because varying both offsets would result in an extremely large number of cases to be evaluated. Such assumption proved to be reasonable, as we will see in Section IV that the resulting model fits experimental results. Like before, C_3 is obtained by averaging the coefficients of all offsets. In order to measure the C_i^* coefficients, we trigger slotted transmissions with i simultaneous devices. Since this time no offset variation is required, running the experiments is much faster. This allowed us to measure the coefficients up to $i = 5$.

IV. Experimental results and discussion

A. Model validation with experimental data

In this Section we compare the models established above to performance measurements performed on the real-hardware testbed. 10 devices are used to generate a wide range of traffic loads. Both Pure ALOHA and a Slotted ALOHA access built over LoRaSync are evaluated. For each generation rate the network runs for 30 minutes, and the throughput is sampled every minute. In each plot errorbars represent 95% confidence intervals computed with Student's t law. The experimental throughput (in Erlangs) is computed by dividing the successful transmission time by the considered duration:

$$T_{\text{exp.}} = \frac{\sum_{\text{pkt}\in\text{received}} ToA_{\text{pkt}}}{\text{duration}} \tag{9}$$

The experimental throughput for Pure and Slotted ALOHA are compared to our models in Figure 3. The usual models that do not take capture effect into account [10] are also provided for the sake of comparison. It is clear that our experimental models faithfully represent the experimental data, while the ones that do not account for capture effect widely underestimate the real-world throughput. For low rates the curves perfectly match, and when the rate increases the model becomes more pessimistic. This is due to the fact that at high rates the probability of a capture event involving many concurring devices increases, and that we have only modeled

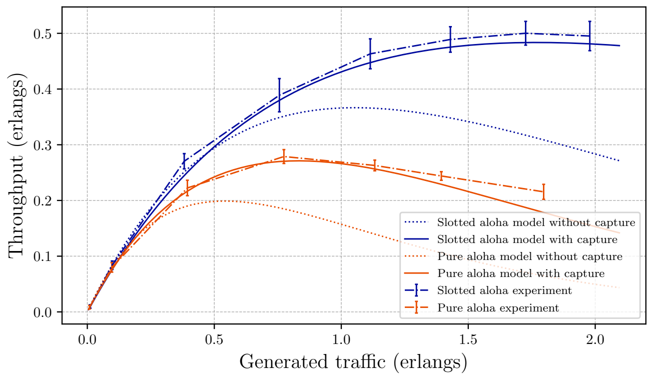


Fig. 3: Throughput model validation with experimental results (10 devices).

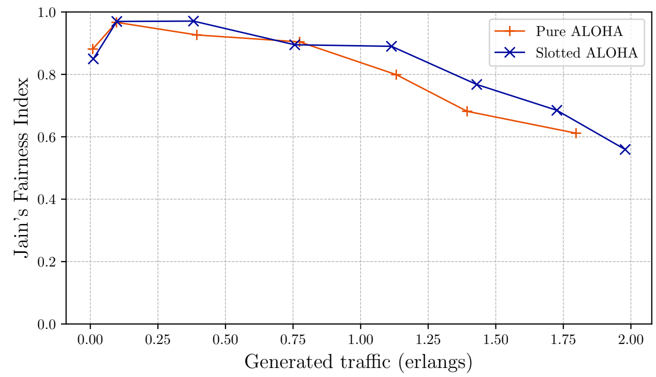
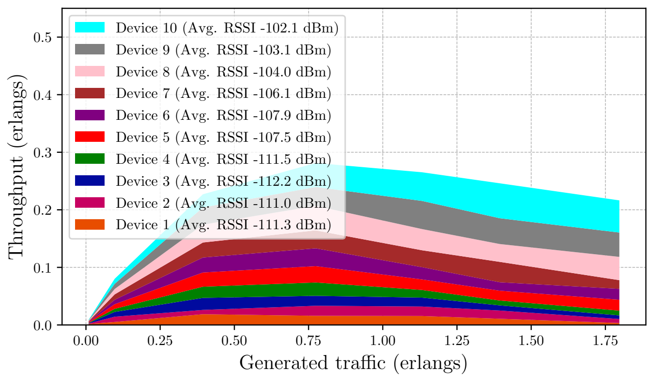
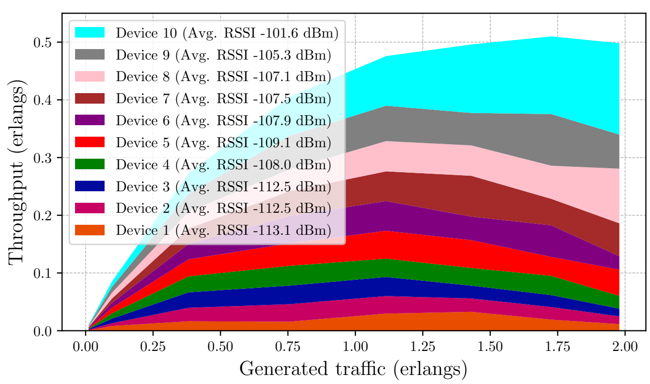


Fig. 5: Jain's fairness index



(a) Pure ALOHA



(b) Slotted ALOHA

Fig. 4: Throughput per device

up to 3 simultaneous devices for Pure ALOHA and 5 for Slotted ALOHA. For generation rates between 0 and 1.5 Erlangs the model falls within experimental errorbars, and is therefore considered to be validated.

B. Impact on the network fairness

It has been shown that the capture effect has a negative impact on the fairness of LoRa networks [28]. To quantify this side effect in our testbed, the contribution of each device to the overall Pure and Slotted ALOHA throughput has been displayed in Figures 4a and 4b respectively. The average RSSI of the successful transmissions of each device is provided and has been used to sort them. It clearly appears that the devices featured with the strongest average signal power at the receiver are favored in terms of throughput. For instance, for a generated load of 1 Erlang, the weakest of the 10 devices participates up to 5.5% of the useful slotted traffic while the strongest produces 16.6%. Therefore, even in our simplistic testbed where all devices are placed at the same location and use the same transmission power, one device may benefit from three times as many successfully demodulated frames as another. This supports the claim that the capture effect may jeopardize the overall fairness of a LoRa network, especially because in a more realistic deployment devices would be much more spread apart which would result in larger RSSI differences. In order to quantify this loss of fairness, we additionally compute Jain's index [13] with our experimental data. Such index is independent of the throughput scale, continuous, bounded between 0 and 1 and applies for any population size. As a result, it is widely used in the networking community to analyze how fairly a given bandwidth is shared between traffic flows. By noting n the number of devices and T_i the success rate for device i, Jain's Fairness Index J is computed as such:

$$J = \frac{(\sum_{i=1}^{n} T_i)^2}{n \cdot \sum_{i=1}^{n} T_i^2} \tag{10}$$

J has been plotted in Figure 5 for the Pure and Slotted ALOHA access schemes. First of all, we notice that no major difference can be witnessed between the Pure and Slotted ALOHA accesses. Besides, we observe that the Jain's index general trend is to decrease when the traffic load increases. This is due to the fact that when more frames are generated, the occurrence probability of capture events increases. Therefore, the devices featured with the highest average RSSI values are able to successfully transmit more frames than the others, which in turns decreases the overall fairness.

C. Discussion

The models in this paper are established with the strong assumption that the capture coefficients are constant. In reality, each coefficient should depend on the RSSI difference between the concurrent packets. This simplification is acceptable for our testbed because all devices are all similar and close one to another, therefore their RSSI difference does not vary much. Besides we focus our analysis on SF7, and it was shown in [20] that this parameter affects the capture coefficients as well. In fact in this preliminary work we are not investigating the causes of the capture effect, but simply quantifying its impact in a simple setup. Further modeling is therefore desired in future contributions to adapt these coefficients to other deployments. It remains interesting to witness that the small RSSI differences occurring in the testbed are sufficient to trigger capture events. We can safely expect that the capture effect would even be more impacting in a realistic large-scale deployment in which devices are spread far apart.

V. Conclusion and perspectives

In this paper we provide experimental models to accurately picture the performances of a LoRa network subject to the capture effect. To achieve this goal, several transmission scenarios are described and their occurrence probabilities are established. Each scenario is repeated for a large number of iterations on an experimental testbed in order to measure the probability of a success. The resulting models prove to be consistent with the performances observed on the testbed. All in all, the capture effect increases the maximum achievable throughput compared to the expectations provided by more classical Pure and Slotted ALOHA models. However the existence of such effect seriously jeopardizes the network fairness in LoRa deployments. As a matter of fact, even in our small scale setup with minimal RSSI variations, Jain's fairness index significantly drops when the traffic load increases.

A more thorough analysis of the capture coefficients is highly needed in future contributions. Indeed we made the hypothesis that these coefficients were constant, when in reality they should be expressed as a function of the RSSI difference between the concurring frames. Tackling this challenge will be mandatory in order to accurately model the throughput of real-life, large-scale LoRa deployments.

References

[1] M. Rizzi, P. Ferrari, A. Flammini, and E. Sisinni, "Evaluation of the IoT LoRaWAN Solution for Distributed Measurement Applications," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 12, pp. 3340–3349, 2017.

[2] B. Reynders and S. Pollin, "Chirp spread spectrum as a modulation technique for long range communication," in *2016 Symposium on Communications and Vehicular Technologies*, Nov. 2016, pp. 1–5.

[3] L. Alliance, "LoRaWAN® L2 1.0.4 Specification (TS001-1.0.4)," 2020.

[4] N. Abramson, "THE ALOHA SYSTEM: another alternative for computer communications," in *Proc. of AFIPS '70 (Fall)*, ser. AFIPS '70 (Fall). Houston, Texas: ACM, Nov. 1970, pp. 281–285.

[5] L. Beltramelli, A. Mahmood, P. Osterberg, and M. Gidlund, "LoRa beyond ALOHA: An Investigation of Alternative Random Access Protocols," *IEEE Transactions on Industrial Informatics*, pp. 1–1, 2020.

[6] T. Polonelli, D. Brunelli, A. Marzocchi, and L. Benini, "Slotted ALOHA on LoRaWAN-Design, Analysis, and Deployment," *Sensors*, vol. 19, no. 4, p. 838, Jan. 2019.

[7] J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "Low Overhead Scheduling of LoRa Transmissions for Improved Scalability," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3097–3109, Apr. 2019.

[8] L. Chasserat, N. Accettura, and P. Berthou, "LoRaSync: energy efficient synchronization for scalable LoRaWAN," 2022.

[9] L. Roberts, "ALOHA Packet System With and Without Slots and Capture," *ACM SIGCOMM Computer Communication Review*, vol. 5, pp. 28–42, Apr. 1975.

[10] R. Rom and M. Sidi, "Multiple Access Protocols: Performance and Analysis," *SIGMETRICS Perform. Evaluation Rev.*, vol. 18, p. 11, 1991.

[11] M. Bor, J. Vidler, and U. Roedig, "LoRa for the Internet of Things," *EWSN*, pp. 361–366, Feb. 2016.

[12] U. Noreen, L. Clavier, and A. Bounceur, "LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation," in *European Wireless 2018; 24th European Wireless Conference*, May 2018, pp. 1–6.

[13] R. Jain, *Art of Computer Systems Performance Analysis Techniques For Experimental Design Measurements Simulation And Modeling*. John Wiley & Sons, May 1991.

[14] Semtech, "AN1200.13 SX1272/3/6/7/8," 2013.

[15] O. Georgiou and U. Raza, "Low Power Wide Area Network Analysis: Can LoRa Scale?" *IEEE Wireless Communications Letters*, vol. 6, no. 2, pp. 162–165, Apr. 2017.

[16] C. Goursaud and J.-M. Gorce, "Dedicated networks for IoT: PHY / MAC state of the art and challenges," *EAI Endorsed Transactions on Internet of Things*, vol. 1, p. 150597, Oct. 2015.

[17] J.-T. Lim and Y. Han, "Spreading Factor Allocation for Massive Connectivity in LoRa Systems," *IEEE Communications Letters*, vol. 22, no. 4, pp. 800–803, Apr. 2018.

[18] D. Croce, M. Gucciardo, S. Mangione, G. Santaromita, and I. Tinnirello, "Impact of LoRa Imperfect Orthogonality: Analysis of Link-Level Performance," *IEEE Communications Letters*, vol. 22, no. 4, pp. 796–799, Apr. 2018.

[19] R. Fernandes, R. Oliveira, M. Luís, and S. Sargento, "On the Real Capacity of LoRa Networks: The Impact of Non-Destructive Communications," *IEEE Communications Letters*, vol. 23, no. 12, pp. 2437–2441, Dec. 2019.

[20] T. Elshabrawy and J. Robert, "Analysis of BER and Coverage Performance of LoRa Modulation under Same Spreading Factor Interference," in *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sep. 2018, pp. 1–6.

[21] B. Daniel, R. Correia, Y. Ding, S. N. Daskalakis, G. Goussetis, A. Georgiadis, and N. Carvalho, "IQ Impedance Modulator Front-End for Low-Power LoRa Backscattering Devices," *IEEE Transactions on Microwave Theory and Techniques*, vol. PP, pp. 1–8, Oct. 2019.

[22] K. Whitehouse, A. Woo, F. Jiang, J. Polastre, and D. Culler, "Exploiting the capture effect for collision detection and recovery," in *The Second IEEE Workshop on Embedded Networked Sensors, 2005. EmNetS-II.*, May 2005, pp. 45–52.

[23] A. Petroni and M. Biagi, "Interference Mitigation and Decoding Through Gateway Diversity in LoRaWAN," *IEEE Transactions on Wireless Communications*, pp. 1–1, 2022.

[24] J. Arnbak and W. van Blitterswijk, "Capacity of Slotted ALOHA in Rayleigh-Fading Channels," *IEEE Journal on Selected Areas in Communications*, vol. 5, no. 2, pp. 261–269, Feb. 1987.

[25] D. Bankov, E. Khorov, and A. Lyakhov, "Mathematical model of LoRaWAN channel access with capture effect," in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Oct. 2017, pp. 1–5.

[26] R. B. Sorensen, N. Razmi, J. J. Nielsen, and P. Popovski, "Analysis of LoRaWAN Uplink with Multiple Demodulating Paths and Capture Effect," in *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, May 2019, pp. 1–6.

[27] S. Kosunalp, P. D. Mitchell, D. Grace, and T. Clarke, "Experimental Study of Capture Effect for Medium Access Control with ALOHA," *ETRI Journal*, vol. 37, no. 2, pp. 359–368, 2015.

[28] B. Reynders, Q. Wang, P. Tuset-Peiro, X. Vilajosana, and S. Pollin, "Improving Reliability and Scalability of LoRaWANs Through Lightweight Scheduling," *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 1830–1842, Jun. 2018.